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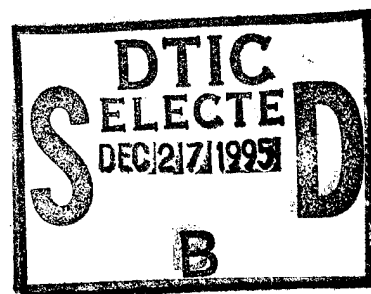
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DIFFERENTIAL GPS FOR PRECISION
APPROACH: COMMERCIAL TECHNOLOGY
AND NAVY/MARINE CORPS REQUIREMENTS

by

Thomas B. Eipp

June, 1995

Principal Advisor: James R. Clynch

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An evaluation of several different Differential GPS systems was performed. This evaluation involved a comparison of system capabilities against the requirements established by the Federal Aviation Administration (FAA) and the DoD requirements. The results showed that most Commercial Off The Shelf (COTS) Differential GPS systems meet or exceed the requirements identified by the DoD.

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DIFFERENTIAL GPS FOR PRECISION APPROACH: COMMERCIAL TECHNOLOGY AND NAVY/MARINE CORPS REQUIREMENTS

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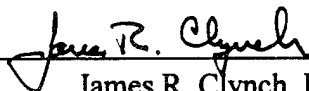## (SPACE SYSTEMS OPERATIONS)

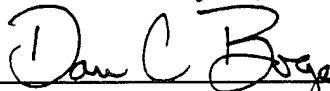from the

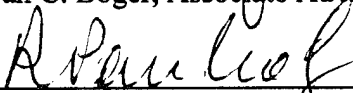## NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Currently, the Department of Defense DoD uses several Precision Landing Systems (PLS) including the Instrument Landing System (ILS), Automatic Carrier Landing System (ACLS), and Precision Approach Radar (PAR). Each system requires different avionics, ground station equipment and are not universally implemented in the different services. This has lead to interoperability problems among the services. Additionally, these landing systems have numerous deficiencies, which include deployablility, manpower requirements, and frequency congestion. Therefore, a new Precision Landing System is necessary to meet DoD requirements.

An evaluation of several different Differential GPS systems was performed. This evaluation involved a comparison of system capabilities against the requirements established by the Federal Aviation Administration (FAA) and the DoD requirements. The results showed that most Commercial Off The Shelf (COTS) Differential GPS systems meet or exceed the requirements identified by the DoD.

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I. INTRODUCTION

A.   GENERAL

The end of the Cold War has forced our political leaders to rethink our national defense plan, resulting in enormous cuts to the Department of Defense's Budget.   In addition to the shrinking budget, the Gulf War established the fact that Joint Force Operations is the way future engagements will be fought, requiring interoperability between the services which had not been a big concern in the past.   To offset the effects of the shrinking budget and the new interoperability requirement, the military is actively looking for ways to exploit readily available commercial technology instead of spending enormous amounts of money developing something exclusively for the military or even one particular service.

Currently, the DoD uses several Precision Landing Systems (PLS) including the Instrument Landing System (ILS), Automatic Carrier Landing System (ACLS), and Precision Approach Radar (PAR).   These systems require different avionics, ground station equipment, and are not universally implemented in the different services, which has lead to interoperability problems between the services.   This, along with the fact that these landing systems have a number of deficiencies, which include deployability, manpower requirements, and frequency congestion, has caused the DoD to look for a new Precision Landing System to meet these requirements.

Today, there is an increasing demand for new and improved Precision Landing Systems in the civilian world as well as the military, which has contributed to the development of Differential GPS.   It was not long ago that it had been generally accepted that ordinary Differential GPS would not meet the required accuracy performance to be certified under the Navigational Sensor Error (NSE) standard used to define the accuracy standards for the current Instrument Landing System (ILS).   However, with the explosion of new technology in Differential Global Positioning Systems (DGPS) and with the

adoption of the Required Navigation Performance (RNP) concept (or tunnel concept, defined in Chapter III) it has become possible to meet the accuracy requirements using DGPS. This is the basis for this thesis, which will explore the question:

Is Commercial Off The Shelf (COTS) technology in Differential Global Positioning Systems (DGPS) capable of meeting the stringent military requirements?

B.   THESIS DESCRIPTION AND OBJECTIVES

Research work in Differential Global Positioning Systems as precision landing systems is very popular because of the enormous potential of the system and the large profits possible in developing a new precision approach system available to the entire world.   Research into automatic landing systems is one of the top priorities in the commercial sector. The task of automatically landing an aircraft on land or the deck of a moving aircraft carrier requires very exacting navigation and control. Navigation errors that would normally be considered minuscule become unacceptable or even disastrous during an automatic landing.

This thesis will explore commercial DGPS technology to determine the feasibility of using DGPS to satisfy the DoD requirements for its new Precision Landing System (PLS). The objectives of this thesis are as follows:

   ◇ Document FAA and DoD requirements for a Precision Landing System

   ◇ Determine feasibility of using Commercial DGPS systems in the DoD

C.   AIRCRAFT LANDING SYSTEMS

Aircraft landing systems were developed to allow the safe landing of aircraft under adverse weather conditions. Since weather conditions, aircraft avionics, and landing systems vary, the Federal Aviation Authority (FAA) has divided landing systems into two basic classes: Nonprecision and Precision Approaches. The following paragraphs further explain and breakdown these classes.

1. Nonprecision Approaches

An instrument approach is considered a nonprecision approach when the navigation signal does not provide the aircraft with glide path or glide slope information. The only navigation information being provided to the aircraft is lateral deviation (azimuth) from the intended flight path. A VOR (VHF Omni-directional Range) or NDB (Non Directional Beacon) are examples of nonprecision approach navigation aids. Since there is no glide path or glide slope information, the minimum decision height is substantially higher than a precision approach. A typical VOR Decision Height (DH) is 500 ft. Decision Height refers to the Height Above the Touchdown (HAT) zone.

2. Precision Approaches

The difference between a nonprecision approach and a precision approach is that a precision approach provides glide path or glide slope information. In addition, a precision approach navigation aid typically has better lateral accuracy than a nonprecision approach. Because of the vast differences in avionics and pilot capabilities from general aviation to commercial aviation, several different categories of precision approaches were established. Please see Table 1.1 for a description of these different categories as defined by the International Civil Aviation Organization (ICAO).

Category	Decision Height (HAT)	Runway Visual Range	Typical User
CAT I	200 ft	1800 ft	General/Commercial
CAT II	100 ft	1150 ft	Commercial
CAT IIIA	0 - 100 ft	660 ft	Major Airlines
CAT IIIB	0 - 50 ft	150 - 660 ft	Major Airlines
CAT IIIC	0 ft	0 ft	Major Airlines

Table 1.1 Precision Approach Categories Ref. [1]

a. Category I

This is a precision approach with a decision height no lower than 200 ft HAT and a Runway Visual Range (RVR) of at least 550 m. This is the most common category, and typically any aircraft (commercial or general aviation) certified for Instrument Flight Rules (IFR) is capable of this flying this category.

b. Category II

This is a precision approach with a decision height lower than 200 ft HAT, but no lower than 100 ft HAT and a Runway Visual Range (RVR) of at least 350 m. This approach requires the aircraft to have an autopilot, precision decision height determination, and auto throttles. Usually only commercial aircraft are equipped to meet these requirements.

c. Category IIIA

This is a precision approach with a decision height lower than 100 ft HAT, or no decision height and a Runway Visual Range (RVR) of at least 200m. In addition to the CAT II aircraft requirements, the aircraft must have autoland capability. Typically only major airlines fly aircraft with this capability.

d. Category IIIB

This is a precision approach with a decision height lower than 50 ft HAT, or no decision height and a Runway Visual Range (RVR) less than 200m, but not less than 50m. In addition to the aircraft requirements for CAT IIIA, roll out guidance is required for Category IIIB.

e. Category IIIC

This is a precision approach which has no decision height or no Runway Visual Range (RVR) minimum. The aircraft requirements are the same as CAT IIIB.

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II. GPS AND DGPS SYSTEMS

Before describing and comparing the different forms of Differential Global Positioning System (DGPS), it is necessary to review the current radionavigation systems and to understand how the Global Positioning System (GPS) works. In this chapter, an overview of the Global Positioning System, as well as a detailed description of the various forms of DGPS, will be presented.

A. OVERVIEW OF CURRENT RADIONAVIGATION SYSTEMS

It should be understood that navigation systems are used extensively in many aspects of government as well as commercial activities. In fact, the United States government has provided navigation services to the general public for many years, especially those activities that support air and marine commerce.

The civilian sector as well as the military are looking for a Precision Landing System (PLS) to meet future requirements, which should include the capability of automatic landings. Automatic landings place enormous requirements on the Precision Landing System. These requirements include but are not limited to system accuracy. Before starting into Differential GPS, it would be helpful to review several of the radionavigation systems that are currently in operation. They offer various degrees of accuracy due to the type of technology they employ as well as their overall age.

1. Ground Based Radionavigation Systems

a. Radiobeacons

These are radio transmitting stations that operate in the low to medium frequency bands. To navigate using this signal, a Radio Direction Finder (RDF) is used. It measures the bearing of the transmitter with respect to the aircraft or other vessel. There are numerous nondirectional beacons available, which makes them attractive. However, the accuracy of these beacons is typically 3 degrees (2 sigma), which translates

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to approximately a 0.5 nautical mile error at 10 nautical miles and continues to get worse as you move away from the beacon. While this error may seem large, it has been accepted for non-precision approaches into many airports.

b. LORAN-C

LORAN, short for Long Range Navigation, was originally developed for military users. There are approximately 15 LORAN-C chains around the world; a chain consists of a master station and two or three slave stations. This is a hyperbolic system because the receiver is measuring the difference in distance to two known points, which requires the receiver to lie on a hyperbola, with the foci at the two given points. It uses a low frequency signal (center frequency 100 kHz) that allows the receiver to calculate its position by time difference of arrival. The wavelength of the LORAN signal is approximately 1.6 nautical miles, making very precise positioning impossible. The accuracy of the LORAN-C is approximately 0.25 nautical miles, but repeatability (returning the exact same spot) is much greater, usually between 20-100 meters [Ref. 2, p. 140]. In addition, position updates are available only 10-20 times per minute. This system is suitable for enroute navigation and non-precision approaches. However, its accuracy does not meet the requirements for precision approaches and automatic landings.

c. OMEGA

OMEGA is a hyperbolic system like LORAN, except it uses phase difference measurements instead of LORAN's Time Of Arrival (TOA). This system uses Very Low Frequency (VLF) signals in the 10-14 kHz range. The advantage of using VLF is that only eight transmitting stations are required to cover the entire earth. A disadvantage of VLF is that its wavelength is approximately 16 miles, giving a position accuracy in the range of two to four nautical miles. The accuracy of this system doesn't meet the requirements for any type of approach.

d. VOR, VOR/DME, TACAN

VHF Omni-directional Range (VOR), Distance Measuring Equipment (DME), and Tactical Air Navigation (TACAN) provide essential guidance for enroute navigation within the United States. VOR, VOR/DME, and TACAN provide the aircraft with bearing and range with respect to the ground installation. VOR only provides bearing information to the aircraft. VOR and VOR DME use VHF frequencies in the 112-118 MHz range with a channel separation of 50 kHz [Ref. 2, p. 162], while TACAN uses L-band UHF frequencies. Both UHF and VHF signals are line of sight, limiting the effective range to approximately 200 nautical miles at an altitude of 20,000 feet. There are a large number of these systems across the United States. Therefore coverage and availability are very good. Bearing accuracy for these systems is approximately 1.4 degrees, which equates to 0.25 nautical miles at a range of 10 nautical miles. The relative and repeatable accuracies are approximately 0.35 degrees, which equates to 0.063 nautical miles at a range of 10 nautical miles. The range measuring error is approximately 0.1 nautical miles. Position updates are available virtually continuously from these systems, and they are very accurate systems. However, they still don't meet the stringent requirements for automatic landings.

e. Instrument Landing System

The Instrument Landing System (ILS) ground system consists of three main parts, the localizer giving azimuth information, glide path transmitter giving elevation angle, and three markers (outer, middle, and inner markers) giving distance information as the aircraft passes. This is the current precision approach system used through out the United States and most of the world. This system operates in the same VHF frequency band as VOR/DME. It is fully capable of providing the navigation accuracy required for automatic landings. However, there are several disadvantages that make it unsuitable for the future. First, it only has forty channels, which can cause a problem when operating in an area where airport density is high. Next, there can be frequency interference with FM

radio stations using the upper part of the FM band. In fact, this is already happening at many overseas locations. Finally, the complex antenna arrays used by ILS are very bulky and require level ground several hundred meters in front of the antenna. This can cost a great deal of money and makes it unsuitable for some airports. These weaknesses have caused the International Civil Aviation Organization (ICAO) to decide that the ILS would be replaced by better landing systems.

f. Microwave Landing System

The Microwave Landing System (MLS) uses a Time Reference Scanning Beam system. The so called "to-fro" principle is used to determine all angular measurements. Basically, a fan beam is scanned through the approach path. An aircraft receiver can detect this beam as it scans from one side ("to" pulse) then back in the opposite direction ("fro" pulse). It operates in the 5.03 to 5.09 GHz range [Ref. 2, p. 182]. This eliminates many of the problems associated with the ILS. It is extremely accurate and is fully capable of providing the navigation signals required for automatic landings. However, the United States announced in May of 1994 that the Microwave Landing System will not be fully implemented. This was due to the recent developments in Differential GPS showing great potential for a cost effective alternative to MLS and that MLS development was at least 10 years behind schedule at this point.

2. Space-Based Radionavigation

a. TRANSIT

TRANSIT is a satellite system consisting of at least four satellites in 600 nautical mile polar orbits. This system is operated by the Department of the Navy for military users, but there are many civil users. It provides worldwide coverage. However, due to the low number of satellites and relatively low earth orbit, this coverage is not constant. In fact, the satellites only come into view every 1-3 hours. The system transmits on 150 MHz and 400 MHz frequencies. Typical single satellite position errors

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are approximately 500 meters for dynamic users [Ref. 2, p. 245]. The system was designed for maritime users. Therefore, the position updates are too infrequent for air navigation of any type.

b. Global Positioning System

The Global Positioning System was developed by the Department of Defense to provide 24 hour, worldwide radionavigation service. It consists of 24 satellites in six orbital planes each having four satellites. The satellites transmit on the L_1 and L_2 frequencies,. which are 1575.42 MHz and 1227.6 MHz respectively. This system provides two levels of positioning, the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS level is available to all users and provides 100 meter accuracy. The PPS service has been encrypted, making it available only to authorized users, and provides 15 meter accuracy. These systems provide adequate accuracy for enroute, terminal and non-precision approaches. However, they are still not accurate enough for precision approaches and automatic landings.

c. Differential Global Positioning System

The key to Differential GPS is that the majority of the errors associated with GPS are common among receivers that are relatively close. By placing a receiver at a known position you can measure the majority of the error in the GPS signal and broadcast it to other receivers in the local area. Removing these errors makes Differential GPS accurate enough for precision approaches and suitable automatic landings.

There is an increasing demand for Category III precision approach landing systems both in the civilian world and the military. It was not long ago that it had been generally accepted that ordinary Differential GPS would not meet the required accuracy to be certified under the Navigational Sensor Error (NSE) standard used to define the accuracy standards for the current Instrument Landing System (ILS). However, with the enormous explosion in commercial Differential GPS systems and with the adoption of the

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Required Navigation Performance (RNP) concept (or tunnel concept) it has become possible to meet the accuracy requirements using DGPS.

B. GLOBAL POSITIONING SYSTEM

The Global Positioning System is a radio navigation system that is capable of providing continuous global coverage. This system was designed to provide the Department of Defense with a radio navigation system that would last well into the next century. This is a satellite-based system. The Global Positioning System is composed of three principal segments:

- ◇ Space Segment
- ◇ User Segment
- ◇ Control Segment

Each of these segments will be discussed in the following sections.

1. Space Segment

The Space segment consists of the satellite, its orbit, and the signal it transmits. To provide continuous global coverage, the space segment was designed with four satellites arranged in each of six, 55 degree inclination orbital planes about the earth, for a total of 24 satellites.

a. GPS Satellite

Each of these satellites is composed of more than 65,000 individual parts. The Block II satellite weighs approximately 2,000 lbs and is designed for an on-orbit lifetime of 7 1/2 years which is equal to about 580 million miles traveled. See Figure 2.1 for a picture of the satellite. The satellite can be broken down into the following eight major subsystems [Ref. 3].
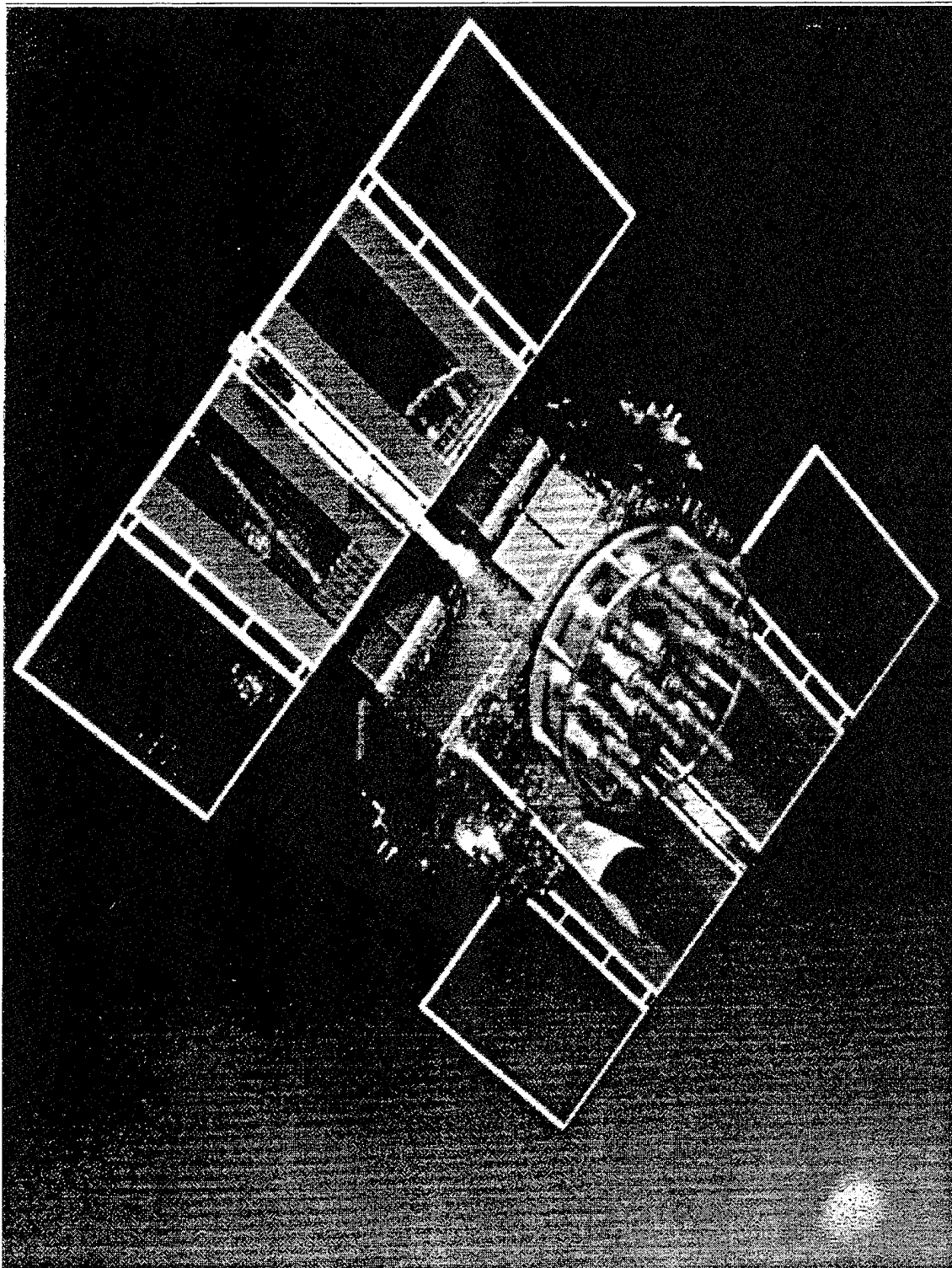
Figure 2.1 Block II GPS Satellite

(1) Orbit injection subsystem. These satellites are put into an initial parking orbit by the McDonnell Douglas Delta II booster rocket. From this initial parking orbit, the satellite fires its Pam-D perigee kick motor. The perigee kick motor burns out shortly after it has been ignited. Once it has burned out the casing is discarded. Once the satellite has traveled 180 degrees to apogee, the apogee kick motor is fired to achieve circular orbit. The apogee kick motor is a Star 37-XF solid rocket built by Thiokol. However, the apogee motor differs from the perigee motor it that it is permanently affixed to the satellite and contributes to the thermal control system by providing an additional absorber and emitter for solar radiation [Ref. 3, p. 130].

(2) Attitude and Velocity Control System (see Figure 2.2). The GPS satellite is three-axis stabilized. It uses momentum wheels to maintain the satellite in its proper orientation with respect to the earth. This is accomplished by adjusting the rotation rates of the momentum wheels. As attitude ajustments are made, the momentum wheels begin to spin faster and faster. The thrusters and the three electromagnet assembly are used to counterbalance the force applied to periodically slow the momentum wheels.
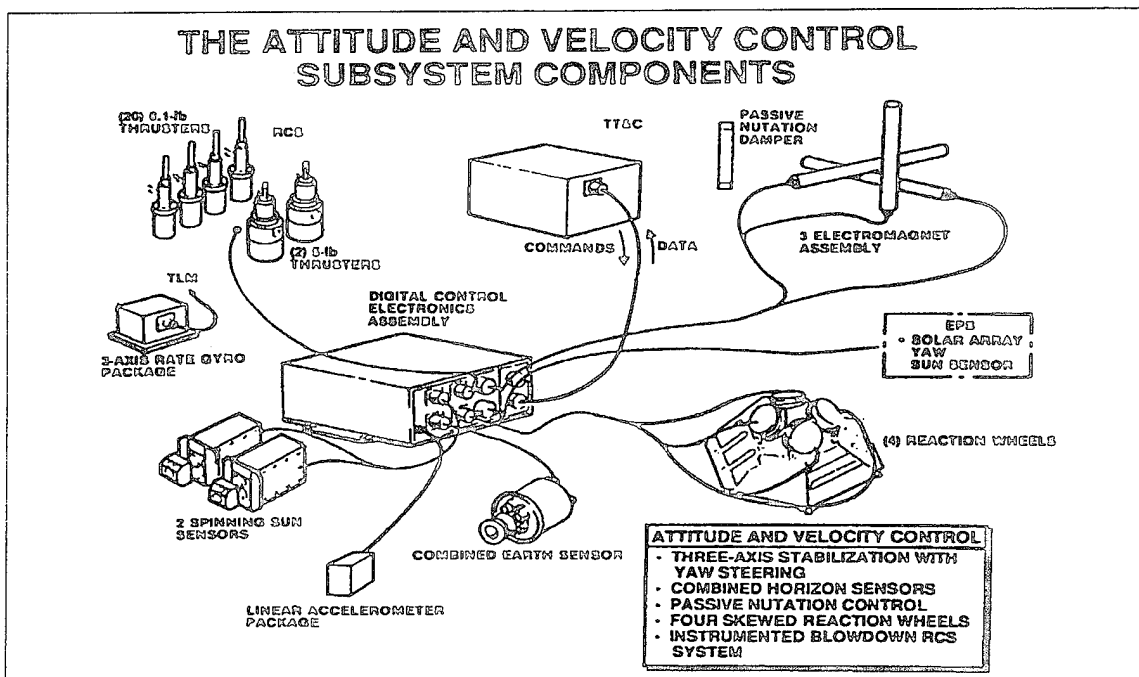
Figure 2.2 Attitude and Velocity Control System From Ref. [3]

(3) Telemetry, Tracking, and Command. This system allows the ground control station to talk to the satellite. This is accomplished via encrypted signals in the S-band range. The uplink frequency is 1783.74 MHz and the down link frequency is 2227.5 MHz. These signals have been designed to be extremely jam resistant. The uplink frequency is used to provide updates to the satellite's ephemeris data and clock correction factors. The downlink frequency is used primarily to provide the ground station with acknowledgments that the corrections have been received.

(4) Electrical Power. Electrical power on board the satellite is generated by two large solar cells. These solar provide 78 square feet of surface area, and the cells were designed so they would provide the satellite with approximately 700 watts of power at the end of the satellite's life. The solar panels track the sun through the entire orbit. However, when the satellite is eclipsed by the earth and operating on battery power, the satellite performs a maneuver to unwind the solar panels and internal cables to allow them to track the sun once again.. Each satellite has three nickel cadmium batteries. They store the excess power generated from the solar cells to provide continuous operation when the satellite is eclipsed by the earth. It is very seldom that the batteries are discharged below 65% of capacity.

(5) Navigation System. This system simply consists of the two cesium and two rubidium atomic clocks onboard the satellite. These clocks are responsible for generating the Coarse Acquisition code (C/A) and the Precision code (P-code) timing pulses. Only one of the atomic clocks operates at any one time. The other three are back-ups and are powered up only upon failure.

(6) Reaction Control System. It is composed of the two, five-pound trim thrusters and twenty 0.1 pound attitude control thrusters. This system provides all of the ΔV required to maintain the proper orbit and attitude if the attitude control system is unable to meet these requirements. All thrusters are hydrazine propellant thrusters. Hydrazine is not extremely efficient, with a specific impulse of approximately 220

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seconds. However it was chosen because of its easy storage requirements and because, when burned it produces simply water and ammonia.

(7) Thermal Control. The electronics and atomic clocks were designed to operate at room temperature. Therefore, the thermal control system must maintain the internal portion of the satellite at nearly constant temperature. The satellite has seven thermostatically controlled louvers that open and close automatically to maintain a constant temperature. In addition to the louvers, goldized mylar-kapton insulation blankets are applied. In some places on the satellite, there are up to 13 layers of insulation. "According to the thermal experts who masterminded the spacecraft design, if they carefully wrapped a 1-pound block of ice in 13-layer mylar-kapton insulation blanket and placed it on the Santa Monica pier, one year later they would still find ice inside!" [Ref. 3, p. 135]. Finally, there are several resistance heaters placed throughout the spacecraft to help maintain the constant temperature required by the electronics and atomic clocks.

(8) Structure (see Figure 2.3). The satellites are composed primarily of aluminum. They use hexagon cells modeled after the bumblebee honeycomb, which are bonded with thin sheets of aluminum to provide light weight and very rigid structure.

b. Satellite Orbits

There are four satellites in each of the six circular orbital planes with an inclination of 55 degrees and an orbital radius of 20,200 km. The high orbital altitude allows for polar coverage, without a polar orbit. The maximum allowed eccentricity is 0.03 before orbital corrections are made [Ref. 2, p. 273]. The 55 degree inclination was initially chosen for two reasons. The first was because the space shuttle was used to launch the satellites. The second reason has to do with geometry, because two satellite orbits moving in opposite directions intersect at approximately a 90 degree angle. This means very good geometry to the user [Ref. 2, p. 275].

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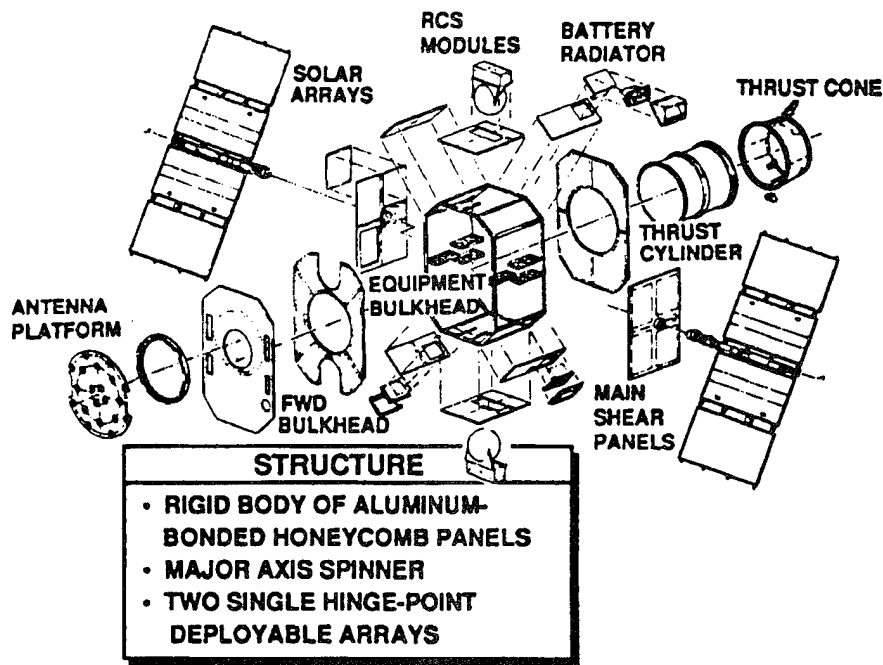
Figure 2.3 Satellite Structure From Ref. [3]

The orbital period is 12 sidereal hours, which equates to 11 hr 58 min. Therefore, the satellite will make two orbits per day. Consequently, the same satellite will appear at a given ground location at the same sidereal time each day. This corresponds to the same satellite appearing in the same position four minutes earlier each calendar day. Each of these satellites transmits a precisely timed binary pulse train and ephemeris data containing its current orbital elements. Currently there are 26 satellites in the GPS constellation. Two of these satellites are Block I satellites. Only one of them still remains in full service. The other 24 are either Block II or Block IIA satellites [Ref. 4].

2. User Segment

The next segment is called the user segment. It simply consists of all the antennas and receiver/processors that are capable of providing position, velocity, and precise

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timing to the user. In order for the user segment to work a minimum of four satellites must be in view of the receiver. Remember that the system was originally developed for the DoD without consideration for civil use. Therefore the signals available to the civilian user only provide limited accuracy compared with the accuracy available from the encrypted military signals (this will be further explained in the GPS signals characteristics section below). It has been the civilian/commercial sector that has been working furiously to develop new and better ways to overcome the civilian sectors limited access to GPS signals which has lead to the explosion of new technology in Differential GPS.

3. Control Segment

Finally, the last segment is called the control segment. Because we don't live in a perfect world, satellite clocks tend to diverge from their original settings, and orbits also tend to degrade. Therefore, they must be continuously tracked and updated. To accomplish this there is a master control station, five monitoring stations, and three ground antennas. The master control station is located at Falcon Air Force Base in Colorado. The five monitoring stations are located at Hawaii, Kwajalein, Ascension Island, Diego Garcia, and Colorado Springs. The three ground antennas are located at Kwajalein, Ascension Island, and Diego Garcia. The monitoring station tracks all satellites within its view. They are continuously accumulating ranging information from the satellites and retransmitting it to the master control station. The master control station uses this data to determine each satellite's precise orbit. Once the orbit has been calculated, each satellite's ephemeris data is updated using one of the ground antennas.

C. GPS SIGNAL CHARACTERISTICS

Each satellite transmits on two L-band frequencies. The primary frequency is L1 at 1575.42 MHz and L2 is at 1227.6 MHz. The two frequencies allow military users to correct for ionospheric errors, which is discussed further in the GPS Errors section of this paper. There are three pseudo-random noise (PRN) ranging codes that are being used.

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The first is Coarse/Acquisition (C/A) code. This code is available only on the L1 frequency. The C/A code is available free of charge to all civilian users in the United States as well as the rest of the world. The C/A code has an error of 100 meters horizontally and 140 meters vertically. This includes a random error called selective availability (S/A) that intentionally degrades the C/A signal to keep the error at these figures with a 95% probability. The main purpose for the Coarse/Aquisition code is to provide the military user with all the appropriate information (i.e., orbital elements, clock behavior, system time) to acquire the Precision code or P-code. However, with the enormous amount of civilian users world wide, the DoD has been forced to recognize that the C/A code is for civilian navigation as well. The C/A has a chipping rate of 1.023 MHz and a 1,023 bit message which it continuously repeats. This establishes the repetition interval at one one-thousandth of a second [Ref. 3, p. 20].

The last two pseudo-random noise (PRN) ranging codes are Precision code (P-code) and the encrypted code (Y-code). The Y-code is identical to the P-code, except it has been encrypted to restrict access to authorized users only. The P-code is transmitted on both the L1 and L2 frequencies. The entire P-code has a length of approximately 2.4×10^{14} bits. With the P-code chipping rate of 10.23 MHz, the P-code would repeat after 267 days, which is just over 38 weeks. The P-code is broken down into week segments and a unique week code is assigned to each GPS satellite. This allows the satellite constellation to include pseudolites (ground based GPS transmitters) to grow to 38 satellites before any changes in P-code assignment would be required. The first 32 codes are reserved for actual satellites, while the remaining codes are reserved for pseudolites. All of these codes are initialized at midnight (GPS time) between Saturday and Sunday.

Since the P-code doesn't repeat for over a week this makes it very difficult to acquire this code in a timely manner. Therefore, a two-step procedure has been developed for the receivers.

The first step starts when the receiver acquires the satellite using the much shorter C/A code. Once this is accomplished, the receiver can start receiving the GPS data stream. The message data is transmitted at a rate of 50 bits/second. The entire GPS message takes 12.5 minutes and is composed of 25 thirty second frames. Each of these frames is further divided into 5 six second subframes. Within each of these subframes a handover word is transmitted. The handover word contains a set of constants that allow the receiver to generate the appropriate P-code.

Therefore the second step for the receiver is to use the handover word to generate the P-code. This allows the receiver to acquire the satellite in a substantially reduced time [Ref. 3, p. 57]. The spherical error associated with the P/Y code is approximately 15 meters.

The Global Positioning System provides two levels of service. They are the Standard Positioning Service (SPS), and the Precision Positioning Service (PPS). The SPS is provided to all users worldwide using the C/A code on the L1 frequency. The PPS consists of both the P-code and the Y-code and is available on both the L1 and L2 frequency. However, due to strategic military concerns only the encrypted Y-code for the PPS and the C/A code for the SPS are continuously transmitted world wide. This limits PPS service to only authorized users.

D.   GPS TIMING

The GPS satellites have atomic clocks onboard to keep track of time. Each satellite has four atomic clocks. Two of the clocks are Cesium and two are Rubidium [Ref. 3, p. 153]. The GPS system time was initiated on January 6, 1980, at 0000 Universal Time (UT). Universal Time (UT) is based upon earth rotation and is referenced from the Greenwich meridian. Since the angular velocity of the earth, ω_E, is not constant, Universal Time is also not constant. GPS uses the USNO Universal Time Coordinate (UTC) system, which uses atomic time scales that are considered to provide a constant time reference. Because of the difference between UTC and UT, UTC is adjusted to UT when the absolute value of the difference between UT and UTC exceeds

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0.9 seconds. UTC is adjusted by an integer value called a leap second [Ref. 5, p. 34]. However, GPS time is not adjusted for leap seconds. Therefore it is offset from UTC by an integer. Since June 17th, 1990 at 0000 UTC time, GPS system time has been given by a Composite Clock (CC), which is a composite of all Monitor Stations and satellite frequency standards [Ref. 4]. The GPS system time is referenced to the master clock at the USNO. One microsecond is the maximum time difference allowed between the GPS system time and the USNO master clock before an adjustment is made. In the past few years the tolerance has been within a few hundred nanoseconds.

E. POSITION DETERMINATION

GPS uses Time Of Arrival to compute pseudoranges. They are called pseudoranges because the receiver clocks have an offset or bias that causes the calculated ranges to be different from the true ranges. To do this each GPS receiver must have in memory a table of binary 1s and 0s representing the unique C/A code of each GPS satellite. The receiver tries to lock onto a satellite by generating an identical code. However, the receiver code will be offset from the satellite code by the length of time it takes the navigation signal to travel to the receiver. The receiver then slews its binary code until its sequence corresponds to the satellite code. This is done through the use of an autocorrelation function which goes from a value of 0 to a value of 1 when the two codes are lined up. The slew offset is the time required for that navigation signal to reach the receiver. The pseudorange can be determined by multiplying this time by the speed of light. This is not the actual range because of the uncertain clock bias of the receiver and the propagation effects on the navigation signal as it passes through the ionosphere and atmosphere.

With a minimum of four satellites' pseudoranges, the receiver can calculate its three dimensional position (X,Y,Z in World Geodetic System WGS-84 coordinates) and receiver clock bias by solving the following four equations.

$$(1) \quad \rho_1 = \sqrt{\left(x_{sat_1} - x_{rcvr}\right)^2 + \left(y_{sat_1} - y_{rcvr}\right)^2 + \left(z_{sat_1} - z_{rcvr}\right)^2} + c\Delta\tau$$

$$(2) \quad \rho_2 = \sqrt{\left(x_{sat_2} - x_{rcvr}\right)^2 + \left(y_{sat_2} - y_{rcvr}\right)^2 + \left(z_{sat_2} - z_{rcvr}\right)^2} + c\Delta\tau$$

$$(3) \quad \rho_3 = \sqrt{\left(x_{sat_3} - x_{rcvr}\right)^2 + \left(y_{sat_3} - y_{rcvr}\right)^2 + \left(z_{sat_3} - z_{rcvr}\right)^2} + c\Delta\tau$$

$$(4) \quad \rho_4 = \sqrt{\left(x_{sat_4} - x_{rcvr}\right)^2 + \left(y_{sat_4} - y_{rcvr}\right)^2 + \left(z_{sat_4} - z_{rcvr}\right)^2} + c\Delta\tau$$

where X_{sat}, Y_{sat}, Z_{sat} are the satellite coordinates and X_{rcvr}, Y_{rcvr}, Z_{rcvr} are the unknown receiver coordinates at a specific time. The speed of the signal propagation is given by c and $\Delta\tau$ is the clock bias.

The accuracy of the clocks aboard the satellites is critical to the pseudorange measurements. In addition to Time of Arrival, GPS is capable of measuring signal phase shift used to determine the position and velocity.

F. GPS ERRORS

Understanding the errors involved this system will allow for the modeling and correcting algorithms to be developed to make the system more accurate. The errors in the GPS system can be broken down into six basic areas:

- Ionospheric Errors

- Tropospheric Errors

- Clock and Ephemeris Errors

- Receiver Noise and Resolution Errors

- Multipath Errors

- Selective Availability

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1. Ionospheric Errors

The ionosphere has been defined as the upper region of the atmosphere ranging from about 50 km through about 1000 km. [Ref. 6, p. 218]. Ultraviolet radiation from the sun partially ionizes this gas in this region, hence the name ionosphere. All electromagnetic signals are affected as they pass through the ionosphere. This effect is a bending and slowing of the signal as it moves through the ionosphere. The index of refraction accounts for this effect and is given by the equation:

$$(5) \quad n_g \approx 1 - \frac{1}{2}\frac{a}{f^2}$$

$$(6) \quad n_p \approx 1 + \frac{1}{2}\frac{a}{f^2}$$

$$(7) \quad a \equiv f_p^2$$

where n_g is the group and n_p is the phase index of refraction, f_p is the plasma frequency (ionosphere), and f is the GPS carrier frequency.

GPS receivers using code measurements to determine pseudoranges are dependent upon the group index of refraction, and these signals will be delayed. Receivers using phase measurements are dependent upon the phase index of refraction, and these signals will be advanced. In either case the amount the signal is advanced or delayed is the same at a given time.

If a receiver is capable of receiving both the L_1 and the L_2 frequencies, then it is capable of performing a dual frequency correction to remove the ionospheric errors. The following is the dual frequency correction equation [Ref. 5]:

$$(8) \quad \rho_{measured} = \rho_o + \rho_{ion}$$

$$(9) \quad \rho_{ion} = -\frac{1}{2}\frac{A}{f^2}$$

$$(10) \quad A \equiv \int a\,ds = \alpha \int N ds$$

Given that ρ_o is the true range, N is the electron columnar content, α is a combination of several constants and assuming code based range measurement, we can substituting equation 9 into equation 8 to get the following equations for two simultaneous (same time and place) measurements with two different frequencies:

$$(11) \quad \rho_1 = \rho_o - \frac{1}{2}\frac{A}{f_1^2}$$

$$(12) \quad \rho_2 = \rho_o - \frac{1}{2}\frac{A}{f_2^2}$$

Equations 11 and 12 can be manipulated algebraically to yield equation 13 which simplifies to equation 14, the dual frequency correction.

$$(13) \quad \left[\rho_1 - \frac{f_2^2}{f_1^2}\rho_2\right] = \rho_o\left[1 - \frac{f_2^2}{f_1^2}\right] + \frac{1}{2}f_p\left[\frac{1}{f_1^2} - \frac{f_2^2}{f_1^2} \circledast \frac{1}{f_2^2}\right]$$

$$(14) \quad \rho_o = \left(\frac{f_1^2}{f_1^2 - f_2^2}\right)\left(\rho_1 - \frac{f_2^2}{f_1^2}\rho_2\right)$$

Equation (14) above only works if the receiver is capable of receiving both L_1 and L_2. However, most civilian receivers are only capable of receiving the C/A code on the L_1 frequency. Since the ionospheric delays can be more than 200 nanoseconds (equates to 60 meters), it is important to consider how civilian/commercial technologies address ionospheric errors.

The Klobuchar model was developed to allow single frequency users to correct for ionospheric errors. It uses a cosine representation to model the daily fluctuation in the Total Electron Content (TEC), where the user latitude determines the amplitude and period of the cosine function. In order to use this model the user must be able to compute his geomagnetic latitude and the angle at which the satellite signal intersects the ionosphere [Ref. 2].

The dual frequency correction can account for almost all of the delay caused by the ionosphere, whereas the single frequency correction is only capable of removing, on average, approximately 60% of the delay caused by the ionosphere.

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2. Troposphere Errors

Again, as the satellite's signal passes through the earth's atmosphere it is slowed slightly. This error is proportional to the amount of atmosphere the signal must travel through. Therefore, signals from a satellite close to the horizon will travel through much more atmosphere in order to reach the earth causing a significantly larger time delay than signals from a satellite that is directly over head. The typical tropospheric delay ranges from 2.5 meters for a satellite directly overhead (an elevation angle of 90°) to 15 meters for a satellite close to the horizon (an elevation angle not less than 5°) [Ref. 6, p. 218]. There are several mathematical correction formulas that model this error. Appendix A describes one of these models.

3. Clock and Ephemeris Errors

Satellite clock error is simply the drift or variation between satellite clocks. This causes an error in the Time of Arrival (TOA), affecting all position calculations. Ephemeris data contains information that allows the receiver to calculate satellite projected positions. The projection position is based upon the ephemeris data that is anywhere from 2 to 24 hours old, which may translate into ephemeris errors between the actual position of the satellite and its modeled position. These errors remain the same whether the receiver is using the PPS or the SPS level of GPS service.

4. Receiver and Resolution Errors

Receiver and resolution errors are determined by the hardware design to include the variations of all the components that make up the receiver, and are a function of the chipping rate. The magnitude of these errors is different for each receiver. However, typical values range from 0.1 to 2 meters [Ref. 2, p.317]. The errors due to receiver and resolution are inversely proportional to the chipping rate, and since the PPS has a chipping rate 10 times greater than the SPS, receiver and resolution errors are smaller for the same receiver when it is using the PPS.

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5. Multipath Error

Multipath exists because the satellite signals may take different routes to the receiver. This is caused by the reflection of the satellite's signal, which in turn, causes the time delay associated with the greater distance traveled. The GPS signal has been designed with several attributes to try to reduce multipath error. First, the navigation message uses right hand circular polarization. Therefore, when the signal is reflected (from many common surfaces) it is reversed to left hand circular polarization reducing the possible interference. Since multipath is more likely to occur with low elevation angles, many GPS receivers ignore or mask signals received from satellites low on the horizon. Because the chipping frequency is ten times larger with the Precise Positioning System, the error due to multipath is less than that of the Standard Positioning System.

6. Selective Availability Error

The United States government intentionally puts extra ranging error into the Standard Positioning System to ensure only authorized users are receiving the full capability of the system. The average amount of error introduced into a SPS range is guaranteed to be no greater than 30 meters and is completely adjustable. This error is introduced by deliberately introducing errors into the atomic clocks and by degrading the navigation message transmitted by the satellites. If the total accuracy of the SPS is going to exceed the accepted value of 100 meters, then the United States government has agreed to notify the International Civilian Aviation Organization (ICAO) at least 48 hours in advance. Figure 2.4 gives a visual representation of the typical range errors associated with P-code, C/A code, and DGPS and their relative weights.
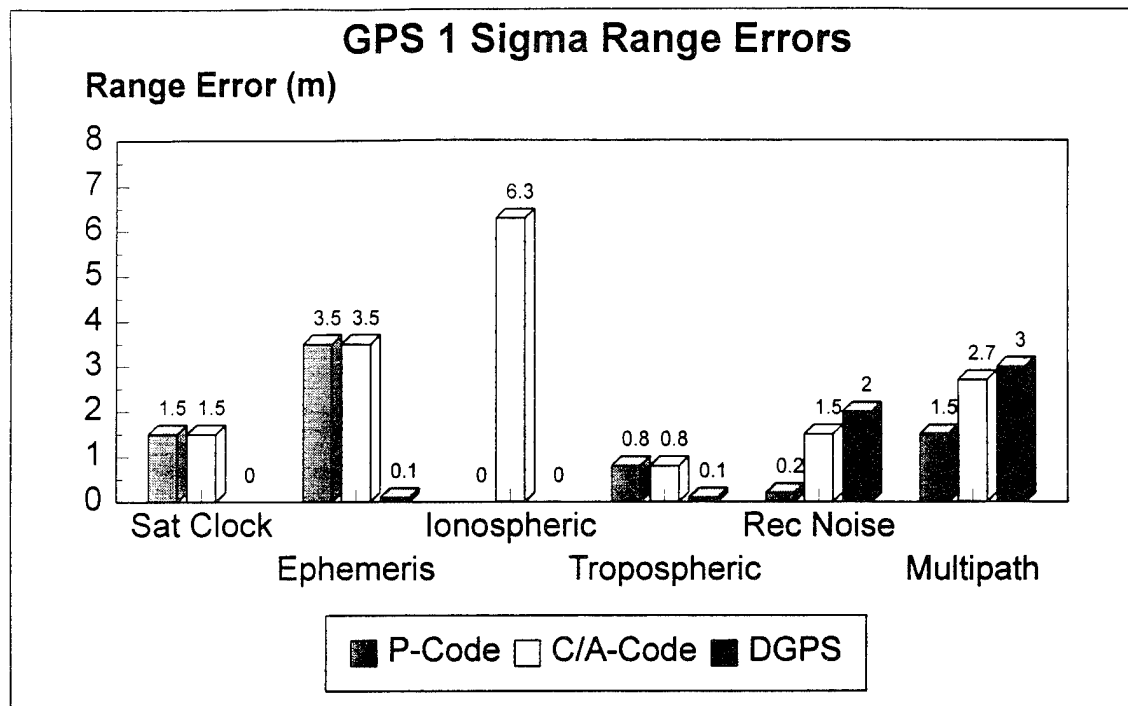
Figure 2.4 1 Sigma Range Error

G. DILUTION OF PRECISION

The are two major factors involved in determining the accuracy of the GPS signal; the first factor encompasses errors in the pseudorange accuracy, which has been discussed in the previous paragraphs. The second factor is the geometrical locations of the satellites with respect to the receiver. This factor is called the Dilution Of Precision (DOP), and links pseudorange accuracy to position accuracy. The relationship between position error and pseudorange error is given by the following equation:

$$(15) \quad \sigma_p = DOP \bullet \sigma_o$$

where σ_p is the standard deviation of the position error and σ_o is the standard deviation of the pseudorange error.

Dilution of Precision is a function of the satellite geometry with respect to the receiver. There are several different types of DOP, which are listed in Table 2.1 below. With the minimum of four satellites in view, the optimal geometry would include one satellite directly over head and the other three spaced 120° apart near the horizon. If this

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were achieved, the Position Dilution Of Precison (PDOP) would be 1.6 [Ref. 3, p. 60]. However to reduce ionospheric, troposperic and multipath errors, receivers typically have a mask angle of about 5 -10°.

Types of DOP	Acronyms	Typical user	Equation
Geometrical	GDOP	Theoretical or Time sync users	$\sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_v^2 + \sigma_t^2}$
Position	PDOP	Air or Space related users	$\sqrt{\sigma_n^2 + \sigma_e^2 + \sigma_v^2}$
Horizontal	HDOP	Maritime users	$\sqrt{\sigma_n^2 + \sigma_e^2}$
Vertical	VDOP	Air related users	$\sqrt{\sigma_v^2}$
Time	TDOP	Time sync users	$\sqrt{\sigma_t^2}$

Table 2.1 Types of DOP After Ref. [3]

The DOP values are simply calculated using combinations of the diagonal elements of the following covariance matrix, which has been transformed into a local north, east, and vertical coordinate system:

$$(16) \quad \begin{bmatrix} \sigma_n^2 & \sigma_{ne} & \sigma_{nv} & \sigma_{nt} \\ \sigma_{en} & \sigma_e^2 & \sigma_{ev} & \sigma_{et} \\ \sigma_{vn} & \sigma_{ve} & \sigma_v^2 & \sigma_{vt} \\ \sigma_{tn} & \sigma_{te} & \sigma_{tv} & \sigma_t^2 \end{bmatrix}$$

H.   DIFFERENTIAL GPS

Up until now the discussion has been limited to stand-alone GPS compared with other forms of navigation. While the accuracy of stand-alone GPS is more than satisfactory for most applications, stand-alone GPS accuracies do not meet the requirements for an aircraft during a precision approach. The civilian community has developed Differential GPS to substantially increase the accuracy to meet precision approach requirements and other applications as well. An aircraft-based Differential GPS system is composed of an airborne receiver, a ground reference station, and a data link

between the two. Differential GPS works by eliminating the errors common to both the receiver and the reference station. The errors that are common to both are ionospheric, tropospheric, satellite clock, ephemeris, and selective availability. There are various forms of Differential GPS, and this research will be limited to the following:

- Standard DGPS

- Narrow Correlator DGPS

- Kinematic Carrier Phase DGPS

- Pseudolites

1. Standard Differential GPS

Standard Differential GPS requires two different GPS receivers. The first receiver is the roving (mobile) receiver, which is trying to obtain the very accurate position using a Differential GPS signal. The second receiver, known as the reference station, is fixed to a precisely known position. Both receivers calculate their positions using the GPS pseudoranges. Since the reference station knows its exact position, it can use satellite ephemeris data to calculate the range error to each satellite in view. The range error for each satellite in view is determined and then transmitted via a data link to the mobile receiver, allowing the mobile receiver to correct for these errors. Please refer to Figure 2.5. One limitation of DGPS is that only satellites which are tracked by both the mobile and the reference station may be differentially corrected.

Of the six basic errors discussed in the GPS Errors section, all but receiver noise and multipath errors are highly correlated between the receivers. This is what makes Differential GPS so effective at reducing the position error. Multipath errors are usually most pronounced when the signal is reflected from a reflective source very close, which would cause only a very short time delay, since the difference in distance would also be small. The GPS receiver uses an autocorrelation function to lock on to the appropriate signal and determine the time delay used in computing the pseudorange. The

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autocorrelation function uses 1 chip length. Therefore, any multipath signal delayed longer than 1 chip will automatically be cut out of this process. Since a close reflected signal will only be delayed in time only a very short period it will produce substantially more interference than a signal that has a longer delay.
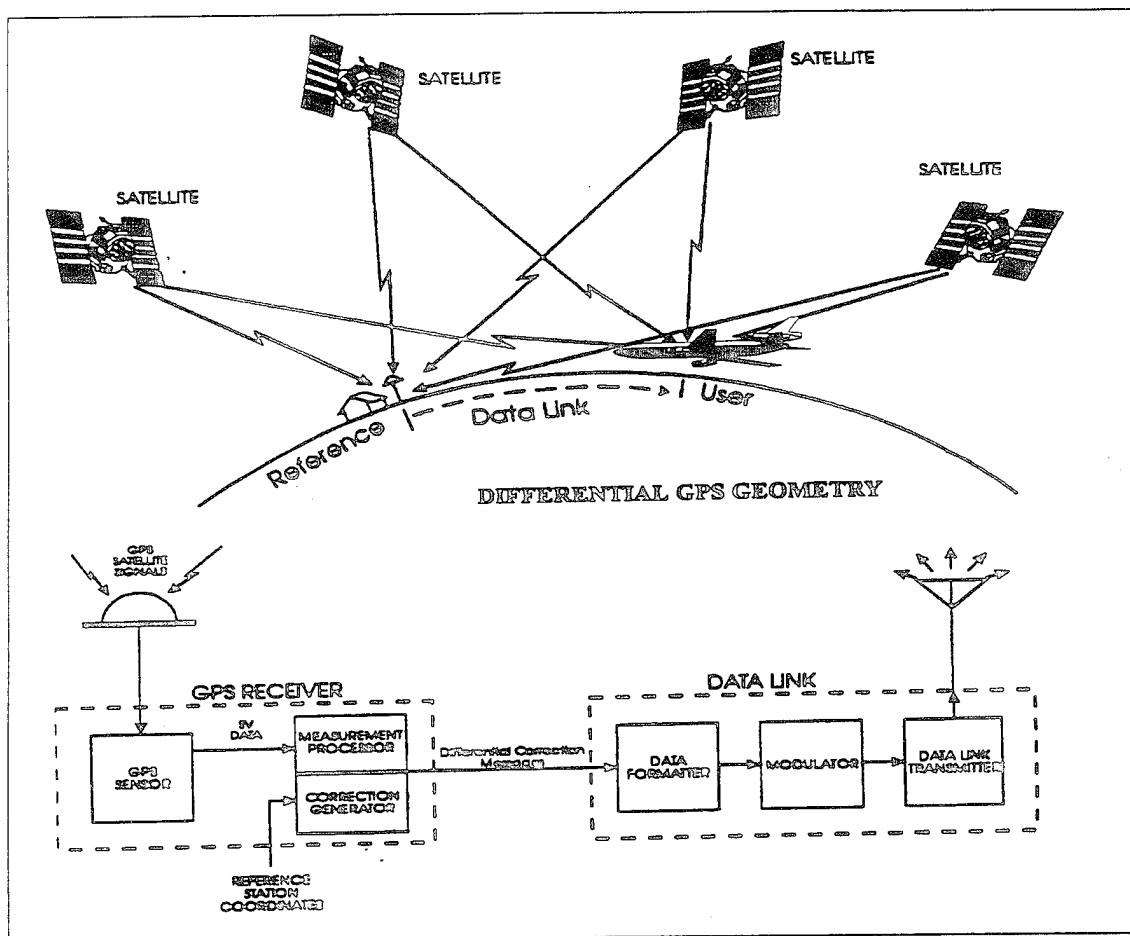
Figure 2.5 DGPS Corrections after Ref. [7]

Ionospheric and tropospheric errors are correlated and the closer the two receivers are the higher the correlation. The GPS satellites are 20,200 km from the surface of the earth. Therefore, over short distances (e.g., 100 km), the signals traveling to two different receivers can be considered to be traveling along parallel lines. So a 100 km difference on the ground equates to an ionospheric penetration point difference of 100 km. Even

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though the ionosphere varies, over these relatively small distances the GPS signals will experience virtually the same time delays and errors.

Selective availability is an error that is intentionally added by the Department of Defense and is a random variable, but the value at any specific time is constant for all receivers tracking the same satellite. This gives a 100% correlation between the two receivers with no data latency (the goal for all DGPS systems) and still remains highly correlated for small latency values associated typical Differential GPS systems. This makes it very easy to remove most if not all of the selective availability error through Differential GPS.

Receiver noise and resolution errors are unit dependent. However, this error tends to be very small, and therefore most receivers are considered to have approximately the same range of errors.

Clock and ephemeris errors originate at the satellite and vary slowly with time. Therefore, even with the small latency associated with DGPS corrections, they can be considered as a constant error between the two receivers and have virtually a 100% correlation in their errors. This makes it possible to remove almost all of these errors as well.

2. Narrow Correlator DGPS

The Narrow Correlator DGPS works on the same principle outlined above for Standard DGPS. It requires two receivers with one of them being a roving receiver with an unknown position, the other the reference receiver with its exact position known. Therefore, the error correction is the same as above except for receiver noise and multipath errors. The time window that a narrow correlator uses is much smaller than a standard GPS receiver. To compensate for this smaller time frame, a narrow correlator receiver looks at a substantially larger bandwidth. A typical standard C/A code receiver uses a 2 MHz pre-detection bandwidth and a 1.0 chip spacing, whereas NovAtel's narrow correlator C/A code receiver uses a 8 MHz pre-detection bandwidth and a .1 chip spacing

[Ref. 8]. Receiver noise is reduced because the increased bandwidth provides sharper edges on the bit stream providing a much better synchronization of satellite and receiver C/A codes. Narrow correlator technology provides noise reduction because the noise component of the early and late signals are correlated and tend to cancel out.

Since multipath signals travel greater distances they require additional time to reach the receiver. Therefore, the narrow correlator reduces the multipath error by closing the window on most of the multipath signals. All of these effects make a narrow correlator receiver more accurate than the Standard DGPS receiver by reducing the receiver noise, multipath and random noise errors.

3. Kinematic Carrier Phase DGPS

Kinematic Carrier Phase DGPS, as its name infers, deals with the position determination of a moving body using carrier phase measurements. It was not long ago that kinematic GPS was considered too complicated to perform in real time as required for all types navigation. This complication was due to computations required by the current algorithms and that most receivers were single channel receivers that scanned all the satellites in view. However, technological advances in computers, multi-channnel receivers, and more efficient algorithms have made it possible. Most real time navigation receivers that use kinematic carrier phase DGPS are based upon relative kinematic DGPS. Relative kinematic DGPS refers to the positioning of a mobile receiver relative to a stationary one. This requires that both receivers observe the same satellites. Using the carrier sinusoidal signal to determine position requires a different observable equation from that used in Standard GPS.

a. Carrier Phase Observable

The carrier signal is continuously transmitted on the L_1 and L_2 frequencies by each satellite. The first step is for the receiver to identify and lock on to each satellite in view. This is done using the C/A code PRN, which is unique for each satellite. Once this

is accomplished , it is easy for the receiver to measure the phase angle and keep a running integer cycle count (a cycle is equal to a 2π radians advance of the carrier phase or one wavelength) based upon the Doppler frequency shift on the carrier frequency. The basic Doppler equation is given by:

$$(17) \quad f_{dop} = -f_x \frac{\dot{R}}{c}$$

where f_{dop} is the Doppler frequency as a function of time, f_x is the transmitted frequency (carrier frequency), $\dot{R}$ is the radial velocity, and c is the speed of light. Since satellite velocity is available through the ephemeris data, the velocity of the receiver can be calculated using the radial velocity and satellite velocity.

At each epoch, the running cycle count and phase angle is available from the receiver. The receiver accomplishes this by integrating the carrier Doppler frequency (f_{dop}). The integration is carried out between epochs, concluding with the receiver making a phase angle measurement. The mathematical relationship is given by the following equation:

$$(18) \quad \phi_n = \phi_{n-1} + \int_{t_{n-1}}^{t_n} f_{dop}(\tau)d\tau$$

where ϕ_n is the accumulated phase at epoch in cycles.

Receivers can typically make carrier phase measurements under dynamic conditions to approximately 1% of a cycle or wavelength, which equates to approximately 2 mm with an L_1 wavelength of 19 cm. However, the integer number of cycles or wavelengths between the receiver and the satellite at the time the receiver locks on to the satellite is unknown. This is called the integer ambiguity (N). Please refer to Figure 2.6 for a geometrical depiction of the phase range. The unknown integer number of wavelengths (N) remains constant while the receiver is locked onto the satellite, which is represented by the equidistant arc from the point R (Unknown Integer Ambiguity Arc). As the satellite moves through its orbit, the receiver is capable of measuring the accumulated phase once the receiver locked onto the satellite at t_0. The $\Delta\varphi_1$ and $\Delta\varphi_2$ represent the measured accumulated phase at times t_1 and t_2 respectively.

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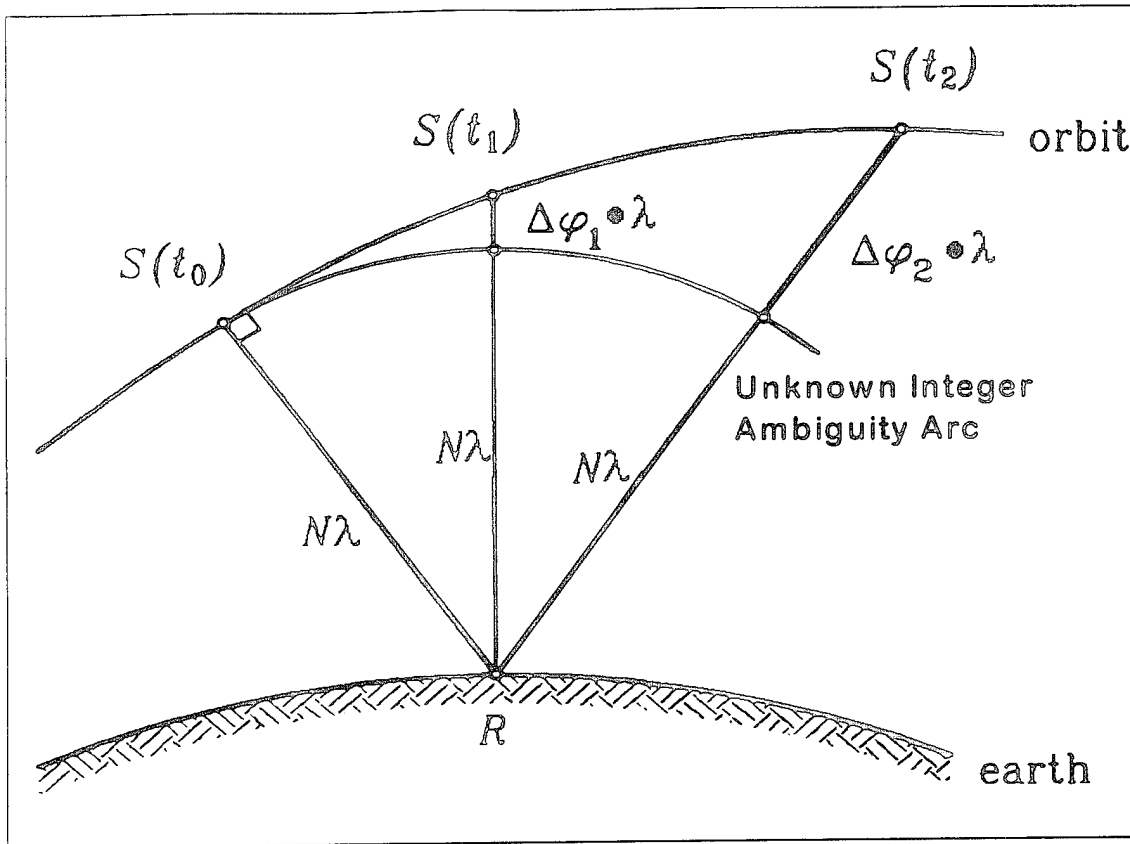
Figure 2.6 Geometrical Depiction of Phase Range From Ref. [5]

The distance between the receiver and the satellite can be expressed as the number of cycles between the two, which if necessary can easily be converted to a distance by multiplying by the wavelength. If we account for noise, integer ambiguity, clock biases, ionospheric, and tropospheric effects, this distance in units of wavelengths can be expressed by the following equation:

(19) $\quad \Phi_r^s = \phi_r^s(t) - \phi^s(t) + N_r^s + S_r + f\tau_s + f\tau_r - \beta_{ion} + \delta_{trop}$

where:

Φ_r^s is the distance between the satellite and receiver in cycles

ϕ_r^s is the satellite transmitted phase as a function of time

ϕ_r is the receiver measured phase of the satellite signal as a function of time

N   is the integer ambiguity

f   is the carrier frequency

τ is the associated clock bias (satellite or receiver)

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β_{ion} is the carrier phase advance due to the ionosphere in cycles

δ_{trop} is the carrier phase delay due to the troposphere in cycles

b. Differencing Techniques

There are several errors and unknowns in the carrier phase measurement observable equation described in the above paragraphs. By using differencing techniques it is possible to reduce or eliminate many of the errors and unknowns. Differencing refers to the techniques we use to reduce or eliminate the common errors in the observable equations through linear combinations of these equations. As discussed in the standard DGPS section above, there is a strong correlation in the ephemeris, clock, tropospheric, ionospheric, and selective availability errors associated with the GPS signal over relatively short distances. There are three levels of differencing, which are single, double, and triple differencing. As you move from single differences to triple differences you continue to reduce the errors and increase the accuracy of the measurement. However, this also limits the solution to the vector between the reference station and the mobile receiver. For navigation systems you need accurate as well as real time information, and both single and double differencing can be done in real time. However, triple differencing involves taking the difference over two different times. Therefore, for real time navigation, this particular differencing technique is not used and will not be discussed further. To try to ease some confusion, superscripts s1, s2, s3 etc. will refer to satellites, subscripts r1 and r2 will refer to receivers, and any s12 or r12 will refer to the difference between satellites or receivers.

(1) Single Differences. There are two different ways that one can take a single difference for navigational purposes.

- Difference between receivers observing same satellite

- Difference between satellites using one receiver

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In each of these cases common errors are differenced out. Figure 2.7 is an example of Single Difference (SD) between receivers while observing the same satellite.
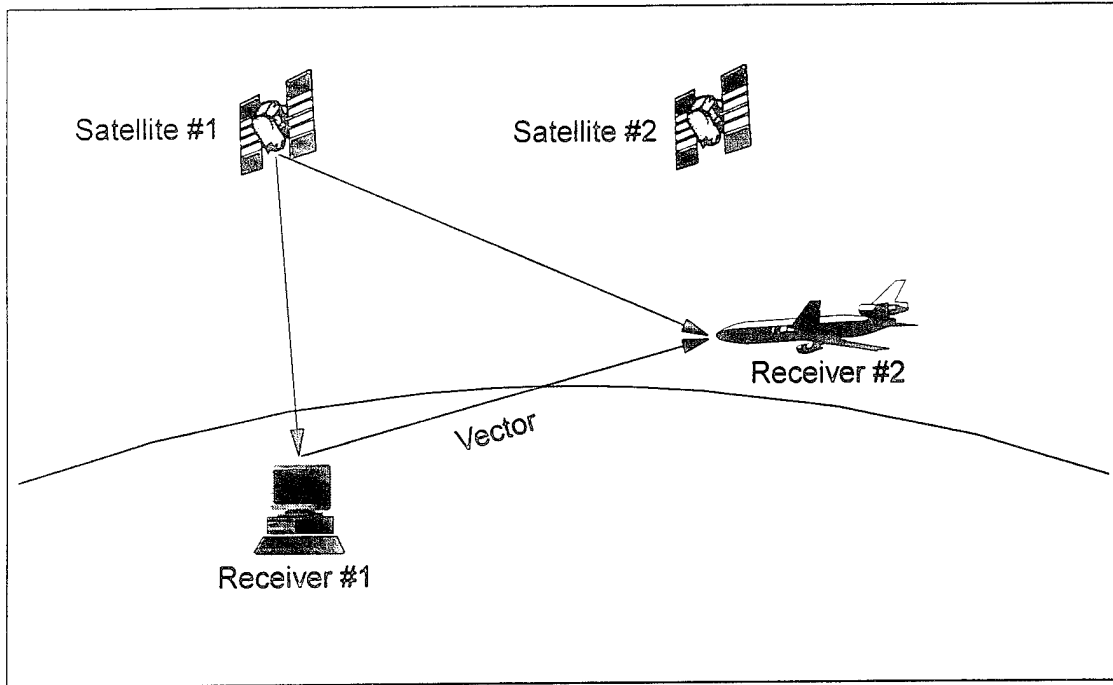
Figure 2.7 Single Differencing

Using our carrier phase observable equation for two different receivers gives us the following two equations:

$$(20) \quad \Phi_{r1}^{s1} = \phi_{r1}^{s1}(t) - \phi^{s1}(t) + N_{r1}^{s1} + S_{r1} + f\tau_{s1} + f\tau_{r1} - \beta_{ion} + \delta_{trop}$$

$$(21) \quad \Phi_{r2}^{s1} = \phi_{r2}^{s1}(t) - \phi^{s1}(t) + N_{r2}^{s1} + S_{r2} + f\tau_{s1} + f\tau_{r2} - \beta_{ion} + \delta_{trop}$$

Taking the difference of these equations yields the following Single Difference (SD) equation:

$$(22) \quad SD_{r12}^{s1} = \phi_{r12}^{s1} + N_{r12}^{s1} + S_{r12}^{s1} + f\tau_{r12}$$

This Single Difference (SD) removes the satellite signal phase and the satellite clock bias. With regard to the ionospheric and tropospheric effects, these also

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are removed, assuming that over relatively short distances these effects are virtually the same. This technique requires us to know the position of the reference receiver and limits us to finding the relative position of the mobile receiver with respect to the known position.

(2) Double Differences. The basis of kinematic GPS is based upon double differences. If we difference any combination of single difference, it produces a double difference. However, the most common way is to difference between two satellites once you have the single difference equation from the two receivers for one particular satellite. Figure 2.8 depicts the double differencing technique.
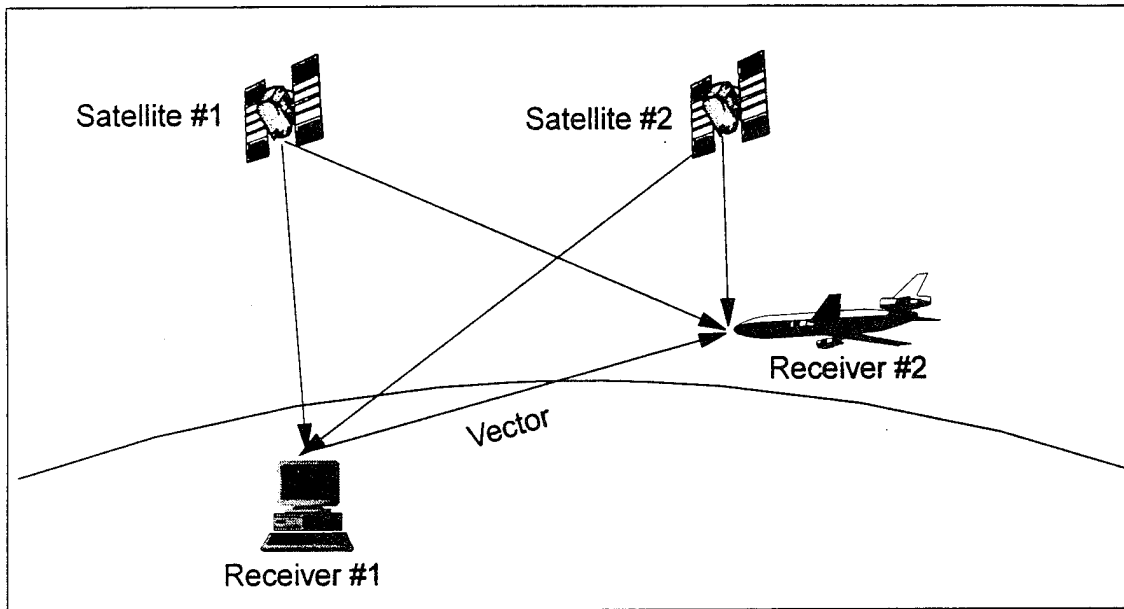
Figure 2.8 Double Difference (DD)

We can now develop another single difference equation for satellite #2, yielding the following single difference equations:

$$(23) \quad SD_{r12}^{s1} = \phi_{r12}^{s1} + N_{r12}^{s1} + S_{r12}^{s1} + f\tau_{r12}$$

$$(24) \quad SD_{r12}^{s2} = \phi_{r12}^{s2} + N_{r12}^{s2} + S_{r12}^{s2} + f\tau_{r12}$$

Taking the difference of these two single difference equations results in the following Double Difference (DD) equation:

(25) $\quad DD_{r12}^{s12} = \phi_{r12}^{s12} + N_{r12}^{s12} + S_{r12}^{s12}$

The Double Difference (DD) has removed the receiver clock bias terms from the equation. What remains is a combined carrier phase term, a combined unknown integer ambiguity for the vector between the two receivers, and a noise term that is composed primarily of the combined multipath effects. It should be noted that N_{r12}^{s12} is still an integer, but represents the unknown integer between the two receivers.

c. Carrier-Smoothed Code

Thus far we have discussed code-based unambiguous pseudoranges, which have a measurement noise (thermal noise) in the 2 meter range, and ambiguous carrier phase pseudoranges, which has a measurement noise in the 2 millimeter range. Many of today's receivers use a carrier-smoothed code pseudorange, which is a blending of code and carrier pseudoranges to filter out most of the measurement noise. One method of accomplishing this is to add an initial condition ($\hat{b}$) to the Accumulated Delta Range (ADR). Please refer to Figure 2.9. The ADR is simply the integrated Doppler (discussed earlier) tracked over a period of time. The initial condition can be estimated by the following equation:

(26) $\quad \hat{b} = \frac{1}{N} \sum_{n=t-N+1}^{t} (\rho(n) - ADR(n))$

Then the carrier-smoothed code (ρ_{smooth}) is given by:

(27) $\quad \rho_{smooth}(t) = ADR(t) + \hat{b}(t)$

The amount of measurement noise reduction can be estimated by the following equation:

(28) $\quad Noise\ Reduction \approx \frac{1}{\sqrt{N}}$

However, the ionospheric effects cause the pseudorange and Accumulated Delta Range (ADR) to diverge in time. Averaging can be done only over short periods of time, with a typical value being 100 seconds. This means the measurement noise is reduced by approximately a factor of 10.
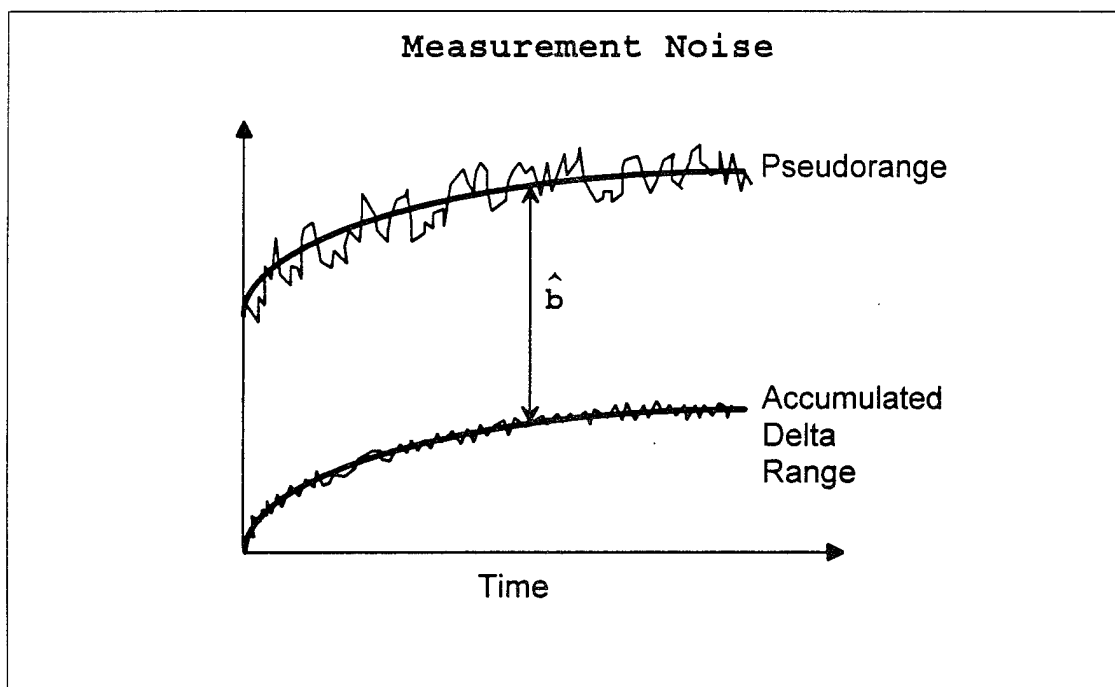
Measurement Noise

Figure 2.9 Measurement Noise difference between ρ and ADR.

d. Integer Ambiguities

Using DGPS and carrier-smooth code a receiver is capable of determining its relative position to within ±1-2 meters. This reduces the integer ambiguity to approximately ± 5-10 wavelengths using the L_1 frequency. It seems obvious to simply iterate through all the possible combinations using a least-squares solution to identify possible integer values. Then we can continue this process until only one solution remains. However, this is inefficient and requires enormous computational power because an ambiguity of ±11 wavelengths would require 23^4 least square solutions to be generated at each epoch [Ref. 9, p. 38].

To reduce this computational requirement and inefficiency, several different techniques have been developed to screen potential integer solutions before any computations are performed. In general all of these techniques have the same basic algorithm. First an initial position is determined. Then a search volume around this position is established and some methodology is used to screen for potential candidates. These candidates are then further tested and, given the selection criteria, finally only one solutions remains.

4. Pseudo-satellites (or Pseudolites)

A pseudo-satellite (false satellite) consists of the same GPS transmitter that is on board the GPS satellite but is ground-based. They may transmit on the L_1 frequency, or be offset from the L_1 frequency just like a regular satellite. Adding a pseudo-satellite has several different effects on the navigation solution.

First it is decreases the Geometric Dilution Of Precision (GDOP). It is the geometry of the satellites that determines much of the accuracy of GPS. The farther apart the satellites, the better the accuracy. Since the pseudolite is located on earth and below the aircraft it significantly reduces the GDOP. Figure 2.10 demonstrates the geometric improvement from putting a pseudo-satellite on earth. It is also another satellite signal and the more navigation signals available the more accurate the navigation solution. Even if the receiver is not capable of monitoring all satellites in view, the receiver has the capability to select the combination of satellites that delivers the best GDOP.

The pseudo-satellite signal does not have to travel through ionosphere and only a small portion of the troposphere compared to the signals originating from space. In addition, the pseudo-satellite is in a fixed known position. All of this adds up to reduce the amount of error in the navigation solution. Furthermore, the pseudo-satellite can function as the reference station for the transmission Differential GPS corrections.

Poor GDOP

Good GDOP
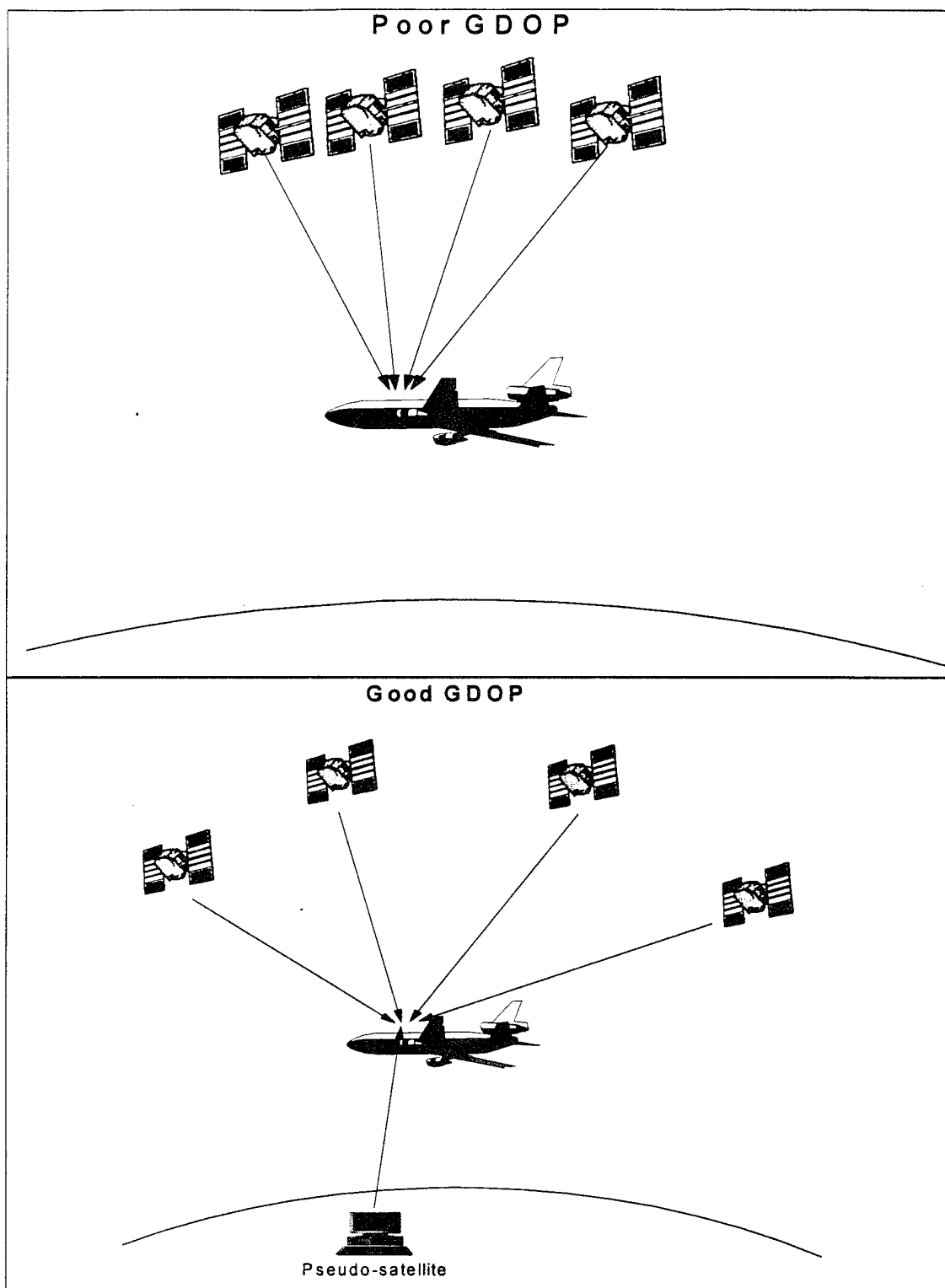
Pseudo-satellite

Figure 2.10 Geometric Dilution Of Precision (GDOP)

However, there are some disadvantages associated with pseudo-satellites. First, if the signal power of the pseudo-satellites is too high, it can jam the navigational signal from the other satellites, which is referred to as the near/far problem. The range of the pseudo-satellites is approximately 60 km (line of site). Pseudolites also require additional aircraft equipment (at least additional antennas).

I. KALMAN FILTERING

There is an error associated with each measurement or observation. Therefore, even with a stationary aircraft it is possible that the observations would show that the aircraft was moving. Hence, filtering is done to reduce this problem. GPS manufacturers use Kalman filters as a means of estimating the position of the aircraft based upon measurements from the GPS receiver (Refer to Figure 2.11).
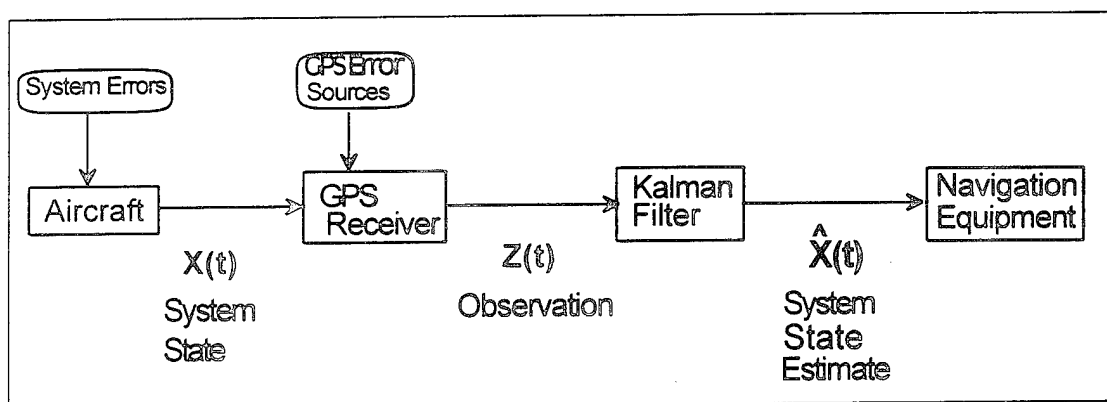
Figure 2.11 Block Diagram Depicting System using Kalman Filter [Ref. 10, p. 3]

The basis behind state estimation and Kalman filtering is that there is a mathematical relationship between the observations $Z(t)$ and the actual system state $X(t)$. To establish this relationship a mathematical model of the measurement has been developed in the following equation:

(29) $\quad Z_i = h(X, t_i) + v_i$

where Z_i is the observed position using GPS, h is a function that relates X to Z_i and v_i is the error introduced into the observation equation by the GPS error sources and the gain matrix being in error.

This equation would work perfectly if the problem was linear. But the motion of the aircraft is not limited to linear motion. In fact, few things in nature are actually linear. The problem with using a non-linear model is this that it requires enormous computations. This is not efficient or practical for real time navigation. Therefore, models are linearized about the most recent state estimate. Refer to Appendix B for some further discussion on Kalman filters.

III. PRECISION APPROACH REQUIREMENTS

A.   DOD MISSION NEEDS STATEMENT

On August 8th, 1994 General Merrill A. McPeak (USAF Chief of Staff) signed the Joint USAF - USN Mission Need Statement (MNS) for Precision Approach and Landing Capability (PALC). This document has been forwarded to the Joint Requirements Oversight Committee (JROC) for review and validation. The next few paragraphs outline the details of this document.

1. Defense Planning Guidance (DPG) Element

The Defense Planning Guidance FY 1994-1999 states "Our investment in innovation must be sustained at levels necessary to assure that U.S.-fielded forces dominate the military-technological revolution." [Ref. 11, p. 10]   This document identifies forward presence and crisis response as essentials elements for our national defense.   To implement these elements the DPG identifies "rapidly deployable, all-weather, day-night, survivable, mobile, and lethal ground combat capability" as a key factor under this new strategy [Ref. 11, p. 41].

2. Mission and Threat Analysis

U.S. forces need to be able to conduct air operations on any suitable surface world wide (i.e., land or sea) under any conditions (peacetime or hostile) with ceiling and/or visibility being the only limiting factor. Therefore, a requirement exists for a precision approach and landing capability (PALC) that is rapidly deployable, survivable, land and sea based compatible, and mobile which is capable of operating 24 hours a day in all type of weather and terrain conditions. The Mission Needs Statement (MNS) states "None of the existing systems comes close to satisfying the mission need for world wide deployment and interoperability between the services." [Ref. 12, p. 1]   The optimal solution is a universal DoD system that is the same for all the services, replacing the

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current service unique systems that hamper joint operations. The system would incorporate the same training, logistics, operations, and procedures to ensure interoperability among the services. This may not be entirely possible because of the vast differences between land and sea based operations for recovering aircraft. However, there is no reason that the avionics for all aircraft shouldn't be compatible.

Due to the recent drawdown and reduction in forward operating locations it is imperative that the new system be developed now. U.S. forces must be ready and mobile if we are to meet the our national security requirements without any degradation from the reduction in forces. The MNS states "There is no direct threat countered by this capability, but PALC is needed to permit the introduction and support of air forces into any land or sea based theater of operations worldwide." [Ref. 12, p. 2] The following is a list of the deficiencies identified in the MNS.

◇ Current systems are manpower intensive and require extensive training of operators and/or support personnel.

◇ Current systems have limited rapid deployment capability, are difficult to transport, require extended periods of time to set up, and require favorable weather conditions during assembly and system checkout.

◇ Current precision approach systems do not provide covert, jam resistant, data transmission and reception capability.

◇ Vulnerability of current systems in hostile areas is very high.

◇ The precision approach systems in use by one or more services are incompatible with the capabilities of aircraft from other Services.

◇ The variety of systems in use makes it difficult to realize logistics and support savings, and results in higher life cycle costs as systems are upgraded.

It is generally accepted that the foremost threat to precision approach and landing systems will come from intercept and geolocating systems capable of identifying, locating, controlling and disrupting these landing aids. The technology required for this type of threat is fairly advanced, and with the breakup of the former Soviet Union it is believed that the threat to PALC is limited to only a few potential enemies at present. However, with the wide proliferation of advanced electronic capabilities, it is easy to believe that the majority of our potential enemies and even terrorists will have this technology in the near future.

Commercial Of The Shelf (COTS) electronic components are susceptible to electromagnetic pulse from nuclear detonations. However, these same electromagnetic pulses would have the same effects on other airfield operations and would render the airfield unusable regardless if the precision approach system is working [Ref. 12, p. 2], thereby negating the need for a precision approach system hardened to meet the electromagnetic pulse associated with a nuclear detonation. Requiring the PALC to meet this requirement could result in enormous costs with a very minimal increase in capability. This is no way reduces the requirement for the PALC to be operated in an environment with Nuclear, Biological or Chemical (NBC) contaminants, to include considerations for operating personnel equipment requirements.

3. Non-material Alternatives

These include changes to doctrine, tactics, training, or organization. To date, there are no known non-material alternatives that can correct for the deficiencies of the current DoD Precision Landing System (PLS).

4. Potential Material Alternatives

Several of the precision landing systems in use today partially meet these requirements. There are also numerous potential alternatives to meet the identified requirements. The following is a list of areas of study for current and potential precision landing systems.

- MMLS

- ILS

- PAR

- GPS

- Passive Autonomous Landing System (PALS)

- Automatic Carrier Landing System (ACLS)

- Instrument Carrier Landing System (ICLS)

- Marine Air Traffic Control and Landing System (MATCALS)

- Autonomous Landing Guidance Program (ALGP)

- Autonomous Precision Approach and Landing System (APALS)

- Austere Airfield Air Traffic Control (AAATC)

- JSOC Jasmine Flower

- Hybrid solutions

5. Constraints

Commercial systems should be used whenever possible for both air and ground systems. This can provide better interoperability throughout the world and also provide significant cost reduction from a research, development and production standpoint. A PALC must also meet the following:

- Manpower Efficient

- Affordable

- Supportable in the field and aboard ship

- Rapidly Deployable

- Operate in adverse terrain

- Operate in adverse weather

- Operate within the defined threat spectrum

Further development of these constraints is provided in the following paragraphs.

a. Logistics

Great effort has been made to consolidate and reduce the logistic demands on the DoD logistics system. Therefore all new systems must not place an additional burden on the system to include support equipment.

b. Transportation

To meet the requirement for a rapidly deployable system, A PLS must be transportable by medium lift helicopters.

c. Mapping, Charting, and Geodesy Support

The Defense Mapping Agency (DMA) has established format standards, and the PLS must be able to accept these standards without any transformation.

d. Manpower, Personnel, and Training

The ideal system will substantially reduce the manpower, personnel, and training requirements. As with logistics, it is unacceptable for the new systems to increase these requirements, especially with the reduction in personnel and budgets.

e. Command , Control, Communications, Computers, and Information

The PLS must capable of complete integration with the C4I architecture. In addition the signal must be jam resistant and covert capable with the situation dictates.

f. Security

The PLS signals must be fully compatible with DoD communication security (COMSEC) requirements. This includes COMSEC devices, procedures, and physical security requirements.

g. Standardization and Interoperability

The PLS must allow for transparent operations with both domestic and international air traffic control systems. In addition, consideration for the interoperability and compatibility with allied nation military forces should be considered. Compliance with the above will be based upon certification testing.

h. Operational Environment

The PLS must be capable of operating autonomously in austere conditions worldwide (i.e., land or sea). In addition, the equipment must be easily operated and decontaminated by personnel NBC equipment.

i. Cost

In today's shrinking budgets, this is a key concern. The PLS must show realistic cost figures and provide a rationale as to why it will provide cost savings over the current system.

6. Joint Potential Designator

Because of all the factors cited above and the fact we have gone from single service operations thinking to joint operations requires the PALC system to function in all of the services as well as all of the aircraft. It would be considered extremely beneficial if the new system could accommodate the differences in current aircraft avionics, but a system tailored to future avionics is satisfactory.

B. FAA PRECISION APPROACH REQUIREMENTS

The basic operational intention of precision landing approach guidance is, and was in the past, to minimize deviations from the intended flight path. Up until last year the only accepted way of measuring precision approach accuracy was through the use of Navigation Sensor Error (NSE). The increasing demand for Category III precision approach landing systems has called for a revaluation of the NSE technique and has led to the development of the Required Navigation Performance concept (tunnel concept) for precision approaches.

1. Required Navigation Performance (RNP)

The Required Navigation Performance concept is a statement of the navigation performance necessary within a defined airspace. The key concept of RNP is the establishment of the aircraft containment surface (the tunnel), which partitions the airspace and delineates the obstacle clearance surface. It establishes maximum errors (deviation from the intended flight path) for the center of gravity (CG) and airframe of the aircraft [Ref. 13, p. 22]. This corresponds to two concentric rectangular tunnels that encompass the approach path of the runway. Please refer to Figure 3.1.
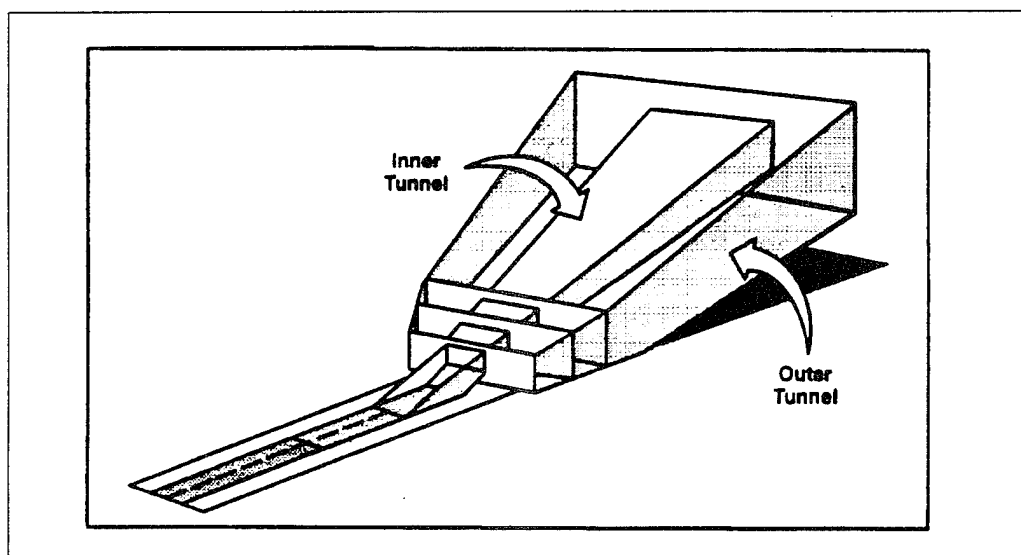
Figure 3.1 Precision approach and landing tunnel boundaries. From Ref. [13]

As the aircraft approaches the runway threshold these tunnels become smaller and smaller. The inner tunnel represents the aircraft center of gravity limits, and the center of gravity must remain within this tunnel 95 percent of the time. The outer tunnel represents a containment surface that no part of the aircraft is allowed to extend beyond. The probability of any part of the aircraft extending beyond the outer tunnel must not exceed one for every 10^7 landings. Hence the RNP is often referred to as the "tunnel concept." This number was determined by examining the number of accidents over a ten year period that were attributed to the ILS and deciding that would be the baseline for future landing systems. The total system is composed of all elements necessary to keep the aircraft position with the established tunnel.

The RNP total system includes both elements on board and external to the aircraft. Therefore, the RNP is based the idea of Total System Error (TSE) and not just Navigation Sensor Error (NSE). Total System Error (TSE) is the rms of the Navigation Sensor Error (NSE) and Flight Technical Error (FTE) (the accuracy with which the aircraft is controlled) as described by the following equation, where NSE includes both air and ground components [Ref. 14, p. B-2].

$$(30) \quad TSE = \sqrt{NSE^2 + FTE^2}$$

The basic concept behind this approach is to minimize the requirements on the Navigation Sensor Error (NSE) by taking advantage of advanced technology which has given us the capability to reduce the Flight Technical Error (FTE). The RNP uses the following parameters to define the total system.

- Accuracy

- Integrity

- Continuity

- Availability

2. Accuracy

Accuracy refers to the actual position of the aircraft relative to the intended position at any given instant in time. This difference in positions is referred to as the Total System Error (TSE). For the RNP concept, the TSE system error must remain within the outer tunnel (containment surface) with the probability of exceeding the outer tunnel to be less than 1.0×10^{-7} per approach [Ref. 15, p. 1B-7]. The accuracy requirements for the total system including inner and outer tunnel requirements are outlined in Figure 3.2.

3. Integrity

Integrity is the trust which can be placed in the correctness of the information that is supplied by the navigation system. The system integrity has been established at 1×10^{-7}, so that less than 1 out of every 10,000,000 approaches would violate the outer tunnel (containment surface) because of the navigation system [Ref. 14, p. D-1]. This applies to all precision landing systems. The integrity of the system includes the failure rate of the transmitting system and the rate the monitoring system fails to detect any out of tolerance signals and provide timely warnings. For Differential GPS systems, the allocation system of integrity has been subdivided into three segments. They are Ground Segment Integrity, Avionics Segment Integrity, and Data Link Integrity. Please refer to Figure 3.3.

The ground segment integrity has been allocated a probability of failure of 3×10^{-8} [Ref. 14]. The primary mission of the ground segment integrity is to prevent an undetected false navigation signal. Therefore this segment includes all possible failure modes of the ground station equipment.

A probability of failure of 6×10^{-8} was allocated to the avionics segment integrity. This segment has been defined as all functions from the removal of the data link CRC to the output of data for navigation. Failures of this type occur in one of two categories. The first is simply a hardware failure. The second occurs when the algorithm for the TSE fails to generate a warning when the aircraft violates the outer tunnel (containment surface).

TOTAL SYSTEM ACCURACY

OUTER TUNNEL 10^{-7} INCIDENT PROBABILITY

GLIDESLOPE = 3.0 DEGREES										HALFWIDTHS IN FEET		
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	200	245	325	425	448	470	564	658	894	1129	1365	1600
VERTICAL	0	NA	65	110	123	135	165	196	272	348	424	500

INNER TUNNEL 95%

GLIDESLOPE = 3.0 DEGREES										HALFWIDTHS IN FEET		
HEIGHT	GPIP	50	100	200	250	300	400	500	750	1000	1250	1500
LATERAL	27	51	75	110	118	125	158	192	275	358	442	525
VERTICAL	0	NA	15	32	36	40	51	62	89	116	143	170

Labels: ±500', ±1600', ±525', ±170', ±425', ±110', HAT = 200', HAT = 100', HAT = 50', 1500', 3000', ±27', ±75', TD BOX AC-20-57A, ROLL OUT BOX, LANDING GEAR, WING TIP, GO-AROUND, ±165', ±200'

- ONLY ONE TUNNEL NECESSARY TO DEFINE PRECISION APPROACH AND LANDING TUNNEL

INTEGRITY

	CAT I FAF TO 200' MIN	CAT II FAF TO 100' MIN	CAT III 100' TO TD TO ROLLOUT
LOSS OF INTEGRITY OF FUNCTION	1.3×10^{-7}	3.3×10^{-8}	3.3×10^{-9}

CONTINUITY

MINIMUM TIME	CAT I FAF TO 200' HAT 150 SEC	CAT II FAF TO 100' MIN 165 SEC	CAT III 100' TO TD 90 SEC	CAT III AFTER TD 90 SEC
MTBO (HRS)	417 HRS	REDUNDANT AIRBORNE EOM GROUND 1000 HRS	REDUNDANT AIRBORNE EOM GROUND 4000 HRS	REDUNDANT AIRBORNE EOM GROUND 4000 HRS
LOSS OF CONTINUITY OF FUNCTION	10^{-4} PER APPROACH	4.4×10^{-5}	2×10^{-6}	1.7×10^{-7}

Figure 3.2 RNP Total System Accuracy From Ref. [13]

```
┌─────────────────────────────────────────────────────────────────────────┐
│                        ┌───────────────────┐                              │
│                        │ Integrity of Function │                          │
│                        │   Per Approach     │                             │
│                        │    1 x 10⁻⁷        │                             │
│                        └───────────────────┘                              │
```
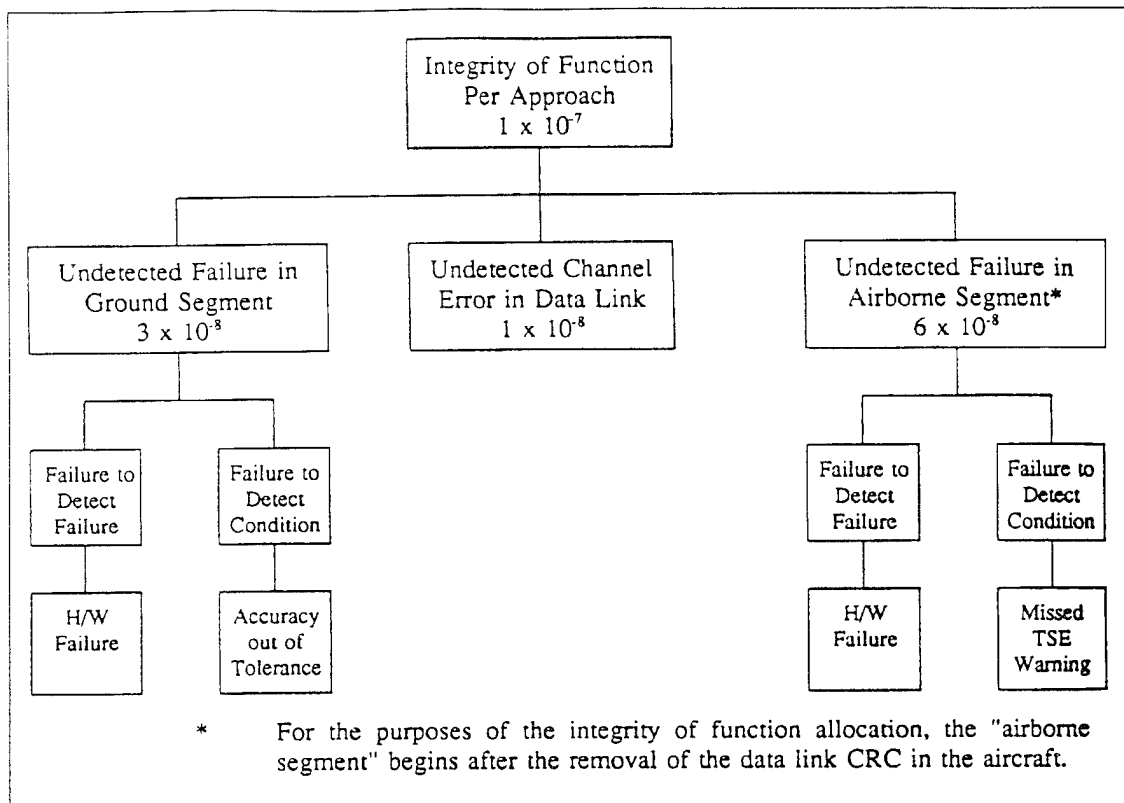

Figure 3.3 Allocation of System Integrity From Ref. [14]

Finally, a probability of failure of 1×10^{-8} has been allocated to the data link integrity [Ref. 14]. This means that over a 2.5 minute period the probability that the aircraft will violate the outer tunnel due to an undetected error must be less than 1×10^{-8}.

4. Availability

Availability is the capability of the entire system to provide the required navigational guidance at the beginning of the intended approach. For a navigation system that has common transmitters for both primary and alternate sites (i.e., GPS based system), the availability requirement is 0.999999 for Category (CAT) III approach [Ref. 15, p. 1B-13]. This equates to a probability of 1×10^{-6} that the system will not be available when the aircraft arrives. It should be noted that scheduled and known outages for satellite maintenance, ground station maintenance, testing, etc. do not count against the availability of the system.

a. *Methodology for Availability Determination*

The rules and regulations that govern Instrument Flight Rules (IFR) operation require primary and alternate sites with landing aids available at both. In the past each airport had its own navigation aid, and therefore the availability of each site was independent. With the development of new navigation aids like GPS, each site is no longer independent of each other, which has added to the availability requirement. Please refer to Table 3.1 below.

Availability Requirements	Category I	Category II	Category III
Primary Site	0.9975	0.9985	0.999
Combined Primary/Alternate Site	0.99999375	0.99999775	0.999999

Table 3.1 Strawman Availability Requirements After Ref. [16]

The following equation was used to determine the strawman availability requirements located in Table 3.1 [Ref. 16, p. 3B-43]:

$$(31) \quad A = A_{(p)} \circ A_{(f)} \circ A_{(m)}$$

where $A_{(p)}$ is simply the availability of all the system components at the airport where the approach is to be conducted. For any ground based system such as the ILS, $A_{(p)}$ is equal to 1 since all required components are located at the airport. This is not the case for space-based systems like GPS since their transmitters are in motion about the earth, and therefore it is possible that $A_{(p)}$ is less than unity. In fact, the complexity involved to calculate $A_{(p)}$ requires a computer model.

$A_{(f)}$ is the availability of the complete system to include degradation and/or shutdown caused from system failures. It is simply the complement of the probability of failure (i.e., 1- probability of failure). This takes into account the Mean Time Between Outage (MTBO) and the Mean Time To Repair (MTTR). $A_{(f)}$ can be calculated using the following formula [Ref. 16, p. 3B-44]:

$$(32) \quad A_{(f)} = \frac{(MTBO - MTTR)}{MTBO}$$

$A_{(m)}$ is the availability of the system to perform routine and/or preventative maintenance when the system is not required for navigational purposes. For ground-based systems this is equal to 1.

The numbers listed in Table 3.1 were calculated based upon several assumptions. The first assumption is that future (i.e., GPS) systems will at least meet the current availability requirements. The second assumption is the MTBO will exceed 2000 hours as required for current ILS Category (CAT) I, II, and III [Ref. 16, p. 3B-44]. Finally, it is assumed that the same level of service was available at both the primary and alternate sites (e.g., both Category III), and that the MTTR is 1 hour.

To understand what these numbers represent in acceptable down times in seconds per year, please refer to Table 3.2 below.

	Category I	Category II	Category III
Primary Site	78,840 sec 21.9 hrs	47,304 sec 13.1 hrs	31,536 sec 8.8 hrs
Combined Primary/Alternate Site (Equivalent MTBO)	197 sec (160,000 hrs)	71 sec (444,444 hrs)	32 sec (1,000,000 hrs)

Table 3.2 Minimum Outage Times From Ref. [16]

5. Continuity of Function

Continuity of Function is simply defined as the ability of the system to provide the navigation information necessary without any interruption during the approach. The total continuity requirement for the entire system has been set at 1×10^{-4} for a 105 second (2.5 minute) approach. Regarding continuity, the total system can be broken down into four segments, which are the Ground Subsystem, the Space Segment, the avionics Subsystem, and Data Link Interference. Please refer to Figure 3.4 below.
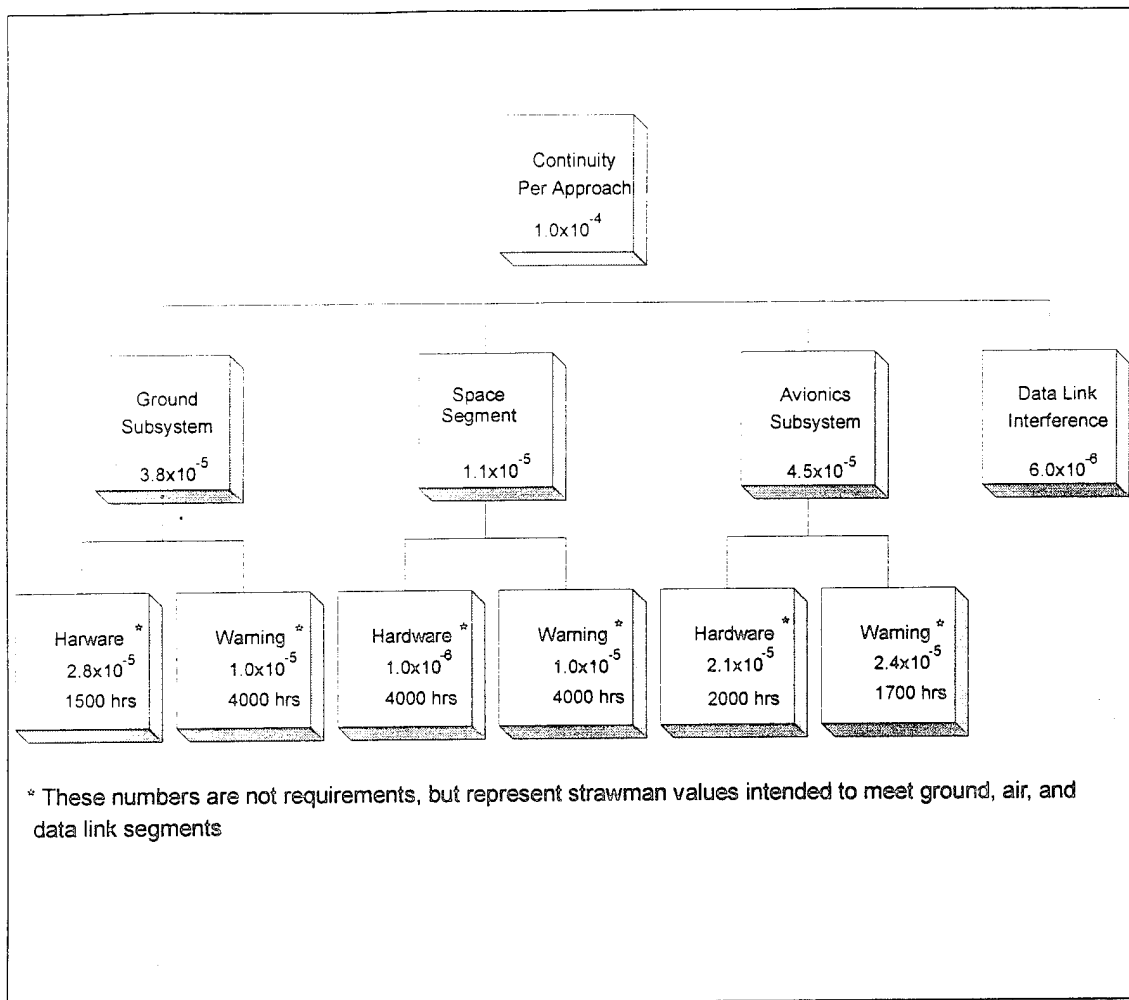
Figure 3.4 Maximum Loss of Continuity per Approach After Ref. [14]

The ground subsystem is composed of all components on the ground including the data link hardware (i.e., router, transmitter). The maximum allowable continuity loss of the ground system includes any failure that would result in the loss of this function. These failures are broken down into two categories, hardware and warning.

The space segment continuity is also broken into hardware failures and warnings. Unlike the other segments of continuity, it is difficult to analyze the effects of these failures on the continuity because the loss of one satellite can vary from virtually no effect to unacceptable dilution of precision. It is this vast difference of effects that makes the allocation of continuity difficult and yet very important because manufacturers will be subject to the actual continuity.

The avionics subsystem continuity is broken down into hardware failure and the total system error warning. The hardware failure includes the GPS receiver, data link receiver, or any other navigation avionics. Continuity loss due to total system error warning can be caused by either lateral or vertical excursion from the approach tunnel. The allocation of failure rates is based on MTBO values derived from the strawman values.

Data link interference has been assigned a failure rate of $6x10^{-6}$. This only includes the errors that occur in the transmission of the RF signal between the ground station and the aircraft. It should be noted that it is possible to increase the data rate in order to meet this demanding continuity requirement.

6. RNP Tunnel Incident Risk

Figure 3.5 below brings together all of the factors in the RNP concept and shows how the risk is allocated.
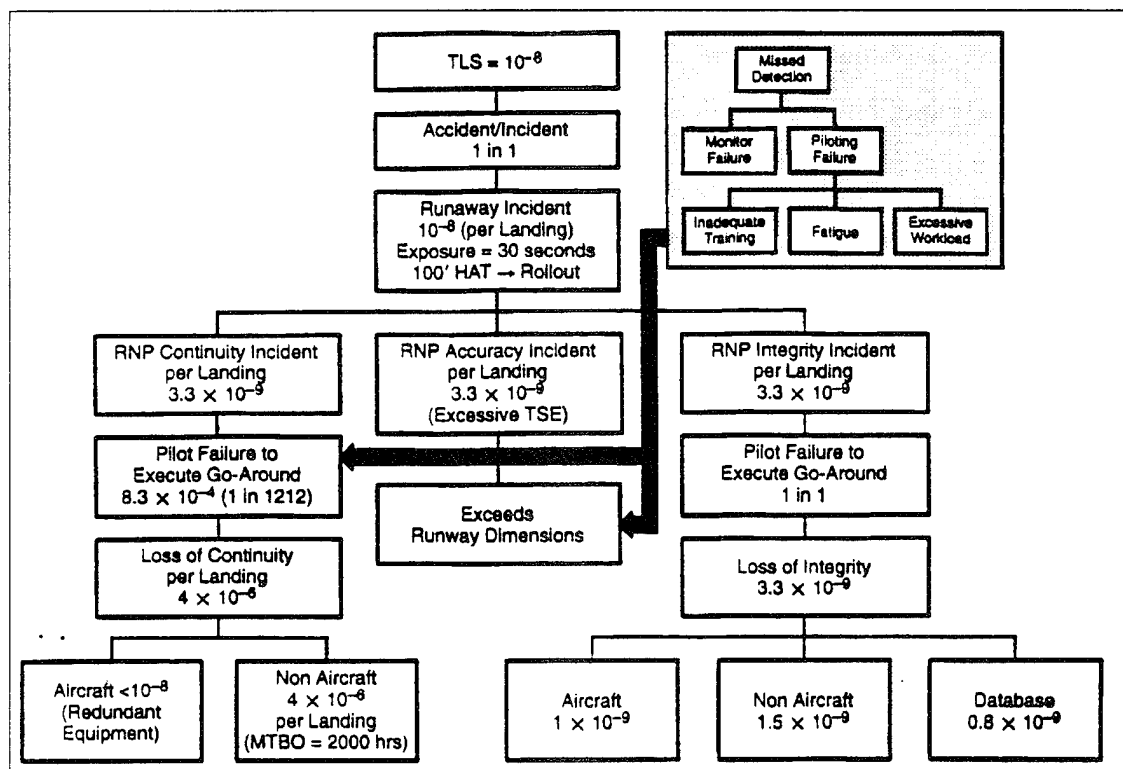
Figure 3.5 RNP Incident Risk for CAT III Operations From Ref. [14]

C.   DOD EVALUATION CRITERIA FOR A PRECISION LANDING SYSTEM

In January 1993, the Precision Landing Study Advisory Group (PLSAG) was formed to oversee the development of the future military precision landing system. The overall goal is to produce the DoD Precision Approach and Landing System (DPALS) Evaluation Criteria. Their first step was the oversight of the development of the Mission Needs Statement discussed earlier. Next, the Precision Approach Study Team (PAST) was formed. Their mission is to mesh the operational and technical viewpoints into the DPALS Evaluation Criteria based upon the PALC MNS. Cost and Effectiveness Analyses are being performed for the DPALS study to facilitate a smooth transition from the study to the Cost and Operational Effectiveness Analysis (COEA) required by DoD acquisition regulations. Therefore, the evaluation criteria are comprised of parameters from the COEA, which include Military Operations (MILOPS), Functional Objectives (FOs), and Measures of Effectiveness (MOEs). Before proceeding it is important to define these parameters. First, Functional Objectives (FOs) are qualitative statements of what the user wants (e.g., operate in adverse weather). Measures of Effectiveness (MOEs) are quantifiable measures of how well the FOs are performed (e.g., system must operate at 100 ft ceiling) [Ref. 17].

1. Classification of Military Operations

Before developing the evaluation criteria, it is important to understand what are the potential ground-based operation environments that the PLS would be subject to. While it is understood that there are an infinite number of possibilities, the PAST has divided them into four scenarios: Fixed Base, Tactical, Clandestine, and Shipboard, given that no classification is perfect and that overlap is possible. It is possible and very likely that each of these scenarios will have different MOE values.

a. Fixed Base Operations

Fixed base operations are carried out at prepared air fields that have a very small probability of being located near areas of hostile action. In addition they are capable of supporting the most demanding levels of air traffic on a continuous basis. Military and civilian air fields in CONUS and outside CONUS, to include training air fields, are examples of this type of operation.

b. Tactical Deployments

Tactical deployments of operations are made to unprepared areas (e.g., bare base or a Marine Expeditionary airfield). The potential for hostile actions is at least medium or it is located near the battle front. Typically this type of operation lasts from a few days to several months. Air traffic flow is not expected to be as high as fixed base operations. An example would humanitarian relief efforts (e.g., Somalia).

c. Clandestine

Clandestine operations by their nature would be secretive and usually behind enemy lines. They typically involve few aircraft and only for a short period of time. The potential for hostile actions is very high. Therefore, this type of operation requires utmost consideration be given to speed and flexibility. An example of this would be Search and Rescue (SAR) missions.

d. Shipboard

Shipboard operations involve all types of aircraft that are capable of landing aboard ship. It is believed that aircraft carrier landings cover the entire range of expected air traffic. Based upon the situation, it is possible that this scenario could require all of the qualities of the three land-based scenarios. Some examples include Anti-Submarine Warfare (ASW), Amphibious, and Task Force (multigroup) operations.

D. FUNCTIONAL OBJECTIVES AND MEASURES OF EFFECTIVENESS

The Functional Objectives (FOs) and Measures of Effectiveness (MOEs) listed below were developed by the members of the PAST. These are preliminary figures, as the PAST's research is not yet complete. However, these FOs and MOEs provide an excellent basis for evaluation of any proposed precision landing system. When the values were assigned to MOEs some of them were given threshold (TH) and objective (OBJ) values. It is important to understand the difference in these terms. A threshold (TH) is the minimum acceptable performance or value for a particular MOE, while an objective (OBJ) is the goal or performance that we are striving for. The information in the following paragraphs has been extracted from Ref. [17].

1. Safe Landings in Adverse Weather Conditions (FO)

Four Measures of Effectiveness (MOEs) have been chosen to help evaluate this Functional Objective (FO). Table 3.3 contains the specific values assigned to each MOE, and the paragraphs following the table help explain the MOEs and to some extent how they were chosen.

MOE	Units	Fixed Base TH/OBJ	Tactical TH/OBJ	Clandestine TH/OBJ	Shipboard TH/OBJ
Accident Rate	Accident per Approach	1 per 10^8	1 per 10^7	1 per 10^6	1 per 10^7
Decision Height	Feet	100/0	200/100	300/200	100/0

Time to Alarm
    Lateral
    Vertical
	Seconds	5/2
		2/2
			10/5
			5/2
				10
				6
					2/1
					2/1

Availability	Percentage	99.5	99	95	99.9

Table 3.3 MOE Requirements for Safe Landing FO After Ref. [18].

a. Aircraft Accident Rate (MOE)

Aircraft accident rate in this context has been defined as the probability of an accident occurring when the PLS is used and that the major cause of the accident was the

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malfunctioning of the PLS. The numbers in Table 3.3 are considered working numbers as data is being collected on historical military accident rates.

b. Decision Height (MOE)

Decision height is the minimum height above the runway that a pilot is allowed to descend in order to visually acquire the runway environment. Decision heights are dependent upon the capabilities of the landing system used by the airport and the aircraft equipment.

c. Time to Alarm (MOE)

Time to alarm is the time required to identify a guidance fault and indicate the warning to the pilot. Current International Civilian Aviation Organization (ICAO) requirements will be used. These times are given in seconds, for both vertical and lateral navigation errors. For shipboard operations, the Navy currently achieves 2 seconds for both vertical and lateral. Since this meets or exceeds the most stringent ICAO requirements, this will be the threshold, with 1 second as the objective for shipboard operations.

d. Precision Approach Availability Percentage (MOE)

The term availability in this context refers to ability to perform the approach at a given airfield, not just the equipment availability of the PLS. Refer to Table 3.3 for established values.

2. Minimum Support Requirements

The following paragraphs describe each of the MOEs identified for this FO, and please refer Table 3.4 for a summary of these values.

a. Number of Personnel Required to Operate System (MOE)

This MOE was developed for Precision Approach Radar (PAR) or a PAR-based system which requires people to operate the system to provide navigation information to

the aircraft or pilot. A threshold of six and an objective of zero was established. For any proposed DGPS-based alternatives this number is zero, since the personnel requirement for GPS operation has already been established and all proposed DGPS landing systems do not require any additional people to operate the GPS system.

b. Number of Personnel Required to Support System (MOE)

This MOE includes those personnel required to deploy and maintain the system. Current system requirements range from 6 to 36 personnel. However, the threshold has be set at 4 with an objective of 0 (clandestine operation threshold is 2).

c. Preventive Maintenance (MOE)

This MOE takes into account all the preventive and scheduled maintenance requirements to keep the system operational. The threshold has been established as 5 hours every 30 days. The objective is 1 hour every 90 days.

MOE	Units	Fixed Base TH/OBJ	Tactical TH/OBJ	Clandestine TH/OBJ	Shipboard TH/OBJ
Operate System	# Personnel	6/0	6/0	6/0	6/0
Support System	# Personnel	4/0	4/0	2/0	4/0
Preventive Maintenance	Hours per Days	5 per 30/ 1 per 90	5 per 30/ 1 per 90	5 per 30/ 1 per 90	5 per 30/ 1 per 90
Availability	Percentage	99.5	99	95	99.9

Table 3.4 Minimum Support Requirements

3. Adequate System Capacity for Servicing Aircraft (FO)

a. Aircraft Capacity (MOE)

This MOE is the number of aircraft that the system can provide precision approach guidance to simultaneously. The PAR is capable of 2, while the ILS is capable of 5 (3 mile separation). The threshold is 2, with the objective being 5.

b. Coverage (Degrees in Azimuth and Elevation) (MOE)

This MOE establishes areas where precision approach guidance is required. These requirements are stated in azimuth and elevation. Since this is a joint development each of the services provided their requirement thresholds are listed below.

- AF/Army: +/- 10° azimuth, 2°-9° elevation

- Navy (Ship): +/- 30° azimuth, 0°-20° elevation

- Marines: +/- 23° azimuth, -1° to +7° elevation

c. Range (Nautical Miles) (MOE)

This is the range in nautical miles that system is capable of providing precision guidance. Again, each service provided their threshold requirements.

- AF/Army: Threshold is 7 nm, Objective is 20 nm

- Marines: Threshold is 5 nm (will accept 7/20 from above)

- Navy: Threshold is 4 nm (detectability factors a key concern)

4. Security Commensurate with Intended Level of Operation (FO)

A complete analysis of all documentation related to threat and security issues is being performed to assess any issues involving a Precision Landing System (PLS). This FO is applicable to all scenarios. However, special consideration needs to be given to tactical, clandestine, and shipboard scenarios when evaluating new technologies.

a. Range and Probability of Detection (MOE)

This is the range at which the enemy could detect the navigation signal from the PLS. The clandestine scenario is the primary candidate for this MOE, but is also applicable to the shipboard scenario as well. This MOE is not applicable to the fixed base scenario (known position) and probably the tactical scenario, since the enemy will presumably be aware of our activities. However, the use of Low Probability of Intercept

(LPI) technology will diminish the enemy's chance of detection at any range. The majority of signals used by PLS are Line of Sight (LOS), which are typically detectable at 10 nautical miles by ground-based equipment and approximately 200 nautical miles for airborne equipment.

b. Spoofability (MOE)

This is the ability of the enemy to cause erroneous navigation signals to be sent out by the PLS. The highest probability of spoofing is believed to be associated with the tactical scenario because the enemy is presumably aware of the operations and may wish to disrupt landing operations. Usually the enemy needs to be fairly close in order to be effective, which provides the fixed base and shipboard scenarios with a slight advantage. Additionally, if the enemy is spoofing a clandestine scenario, the mission has already been compromised. The relative ease with which the system can be spoofed is the primary concern.

c. Effective Range of Jamming (MOE)

This MOE is concerned with the distance at which a jammer can make the navigation signal unusable. Jamming is not limited to intentional enemy action, it can also be caused by unintentional interference from enemy or even friendly systems. The use of nulling antennas will be considered.

5. Easily Deployable Ground Segment (if required) (FO)

This FO only applies to the tactical and clandestine scenarios and an important goal is to develop a PLS that has no ground segment.

a. Setup Time (MOE)

This MOE is the total time required from delivery of equipment until it is available for a flight check. The following numbers have been established based on input

from all the services. It is expected that these numbers could be traded with the MOE dealing with the number of personnel required to support the system.

- Tactical: 24 hour threshold, 1 hour objective

- Clandestine: 4 hour threshold, 0.5 hour objective

b. Sustainability (MOE)

This has been defined as the amount of time a system can operate on external power before maintenance is required. The following numbers are based upon the knowledge of current systems.

- Threshold of 10 days, objective of 90 days (given a 90% probability)

c. Internal (Battery) Power Operations (MOE)

This is the time that a system is capable of operating from internal (battery) power. This is expected to cover the normal mission duration to include takeoff and return for landing.

- Threshold of 4 hours, objective of 12 hours

d. Transportability (MOE)

This MOE defines the modes of transportation the PLS ground equipment requires to move to the intended area of operation. For systems that are not man-portable, it is desirable to have a roll on/roll off capability for ease of movement.

- Tactical: Threshold is 1 C-130, objective 1 truck

- Clandestine: Threshold airdrop, objective man drop

6. Intangible Factors

In addition to the MOEs listed above, there are several intangible factors that need to considered as well. These include but are not limited to the following:

◇ Interoperability (e.g., inter-service, ICAO, Allied, etc.)

◇ Schedule

◇ Technical Risk

◇ Additional Benefits (e.g., service multiple runways)

IV. EVALUATION OF DGPS PRECISION LANDING SYSTEMS

In this chapter, an evaluation of several Differential GPS Precision Landing Systems (PLS) against the Required Navigation Performance (RNP) and the DoD requirements outlined in Chapter III will be performed. With the rapid development of DGPS technology and the enormous potential for large profits, there are numerous vendors and research institutions proposing various DGPS Precision Landing Systems (PLS). Moreover, the FAA has been sponsoring Stanford University and Ohio University to carry out independent flight test programs to demonstrate the feasibility of Category III Precision Landing System using GPS. In addition, the FAA has selected two contractors, Wilcox and E-Systems, to perform flight test demonstrations in mid 1995. Therefore, this evaluation will focus on the systems developed by these four organizations.

Since all of these systems are Differential GPS systems, many of the requirements outlined by the RNP and DoD are fulfilled by characteristics that are common to all four of these systems. Therefore, this evaluation will be conducted in two parts. The first part will provide a system description/operation as well as discuss any requirements that are addressed by the independent system characteristics. The second section is an evaluation of the common characteristics of all the DGPS systems that address RNP and DoD requirements.

A. STANFORD UNIVERSITY'S INTEGRITY BEACON LANDING SYSTEM

1. System Description /Operation

The Integrity Beacon Landing System (IBLS) is based upon the idea of using "integrity beacons" (pseudolites) to augment the GPS signals. The system is composed of a differential reference station (ground station) and two integrity beacons. Please refer to Figure 4.1. The integrity beacons are placed underneath the final approach path of the aircraft. The transmitted power is approximately $1\mu W$, to ensure it doesn't interfere with

reception of the GPS satellite signals (often referred to as the near-far problem) [Ref. 19, p. 150]. This also limits the reception of the integrity beacon signals within the "bubbles" shown in Figure 4.1. Prior to reaching the integrity beacon bubbles, the aircraft is guided using traditional Differential GPS (C/A code). Once inside the integrity beacon bubbles, there are substantial geometry changes that occur, which allow the aircraft receiver to quickly resolve the integer ambiguities. Once this is accomplished the aircraft switches from conventional DGPS to kinematic carrier phase measurements and its associated centimeter level accuracy.
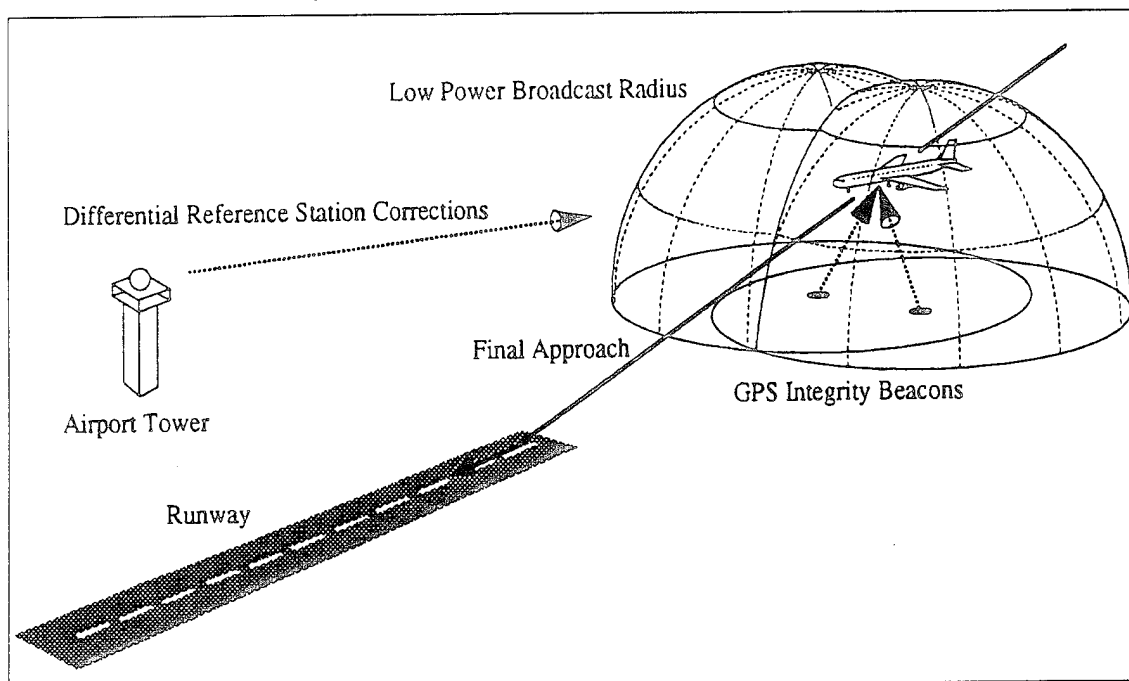
Figure 4.1 The Integrity Beacon Landing System (IBLS) From Ref. [20]

2. Performance Against RNP Requirements

a. Accuracy

Stanford University has performed several hundred precision approaches using their Integrity Beacon Landing System in several different aircraft ranging from a Piper Dakota to a United Boeing 737. This system has exceeded the Total System Error (TSE) defined in the RNP as shown in Table 4.1.

Total System Error	Vertical 100ft	Lateral 100ft	Vertical 50ft	Lateral 50ft
Sigma σ	1.1 m	2.2 m	1.0 m	2.1 m
μ	0.1 m	0.2 m	0.1 m	0.1 m
$|\mu| + 2\sigma$	2.3 m	4.6 m	2.1 m	4.3 m
RNP	4.6 m	22.9 m	TBD	15.5 m

Table 4.1 Total System Error for 110 Autolandings by United Boeing 737 From Ref. [20]

The flight data for the 110 autolandings was plotted against the RNP 95% containment surface. At no time did the aircraft path penetrate the containment surface. Please refer to Figure 4.2 below.
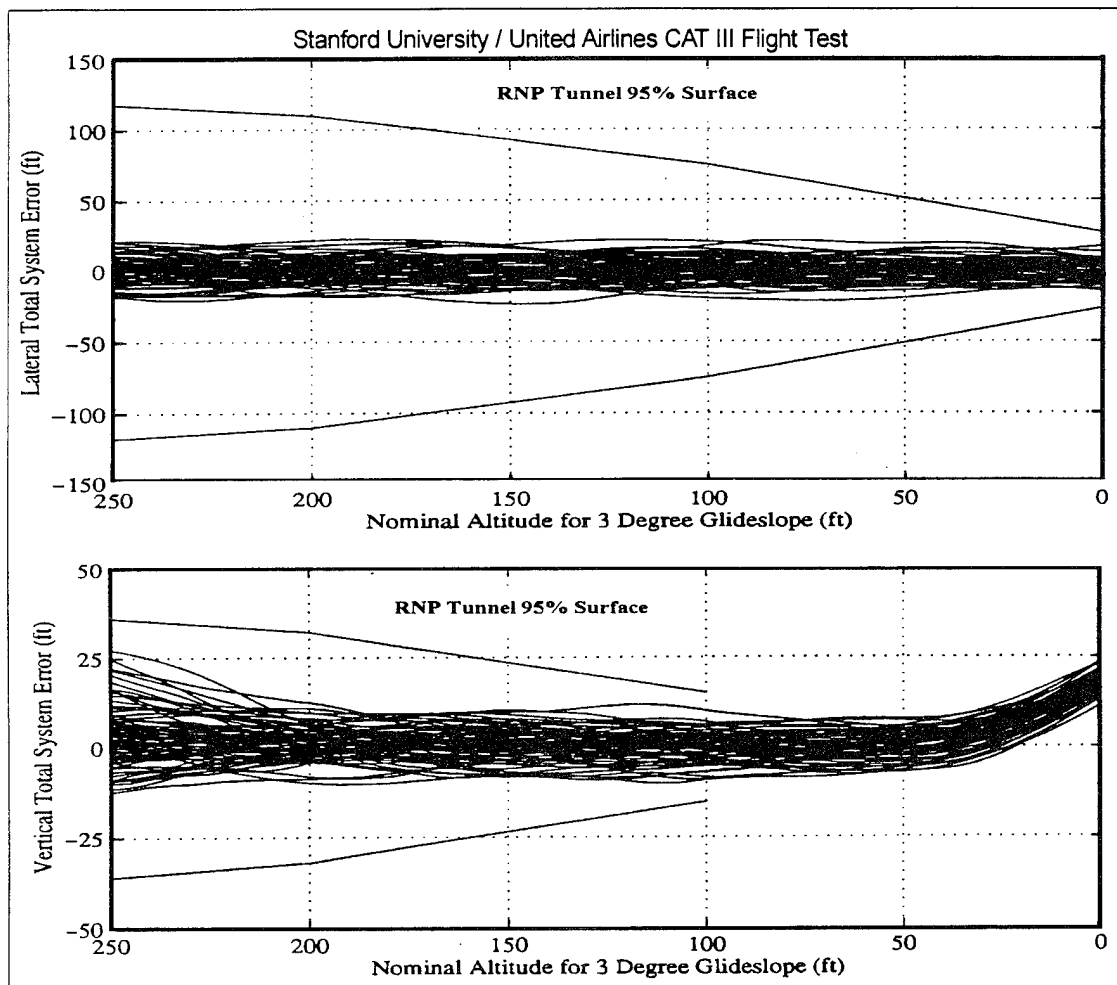
Figure 4.2 RNP Containment Surface vs. 110 Autolandings After Ref. [20]

b. Integrity

Stanford's IBLS uses Receiver Autonomous Integrity Monitoring (RAIM) to achieve a level of integrity that is better than one part in a billion (obtained through analysis, flight trials, and simulation), which exceeds the RNP's requirement of 3.3×10^{-9} [Ref. 20]. It is the extremely accurate carrier phase measurement, which allows very tight thresholds to be set without exceeding the false alarm rate. Refer to Figure 4.3.
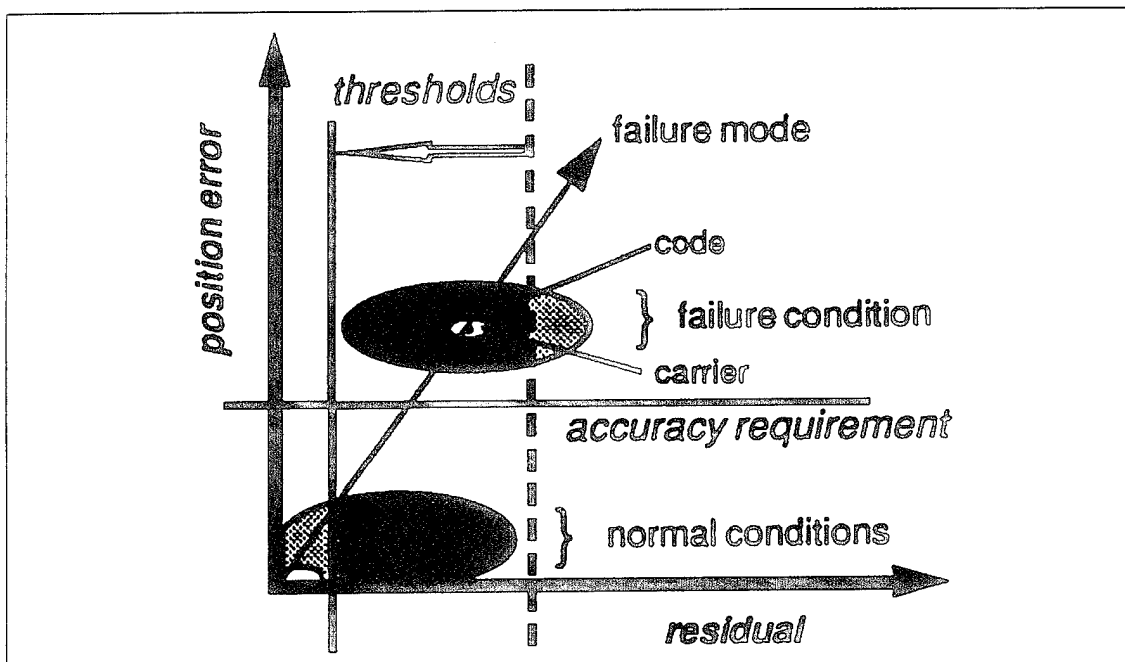
Figure 4.3 Comparison of Kinematic and Code-Based RAIM From Ref. [21]

Figure 4.3 above represents a conceptual plot of position error versus measurement residual for kinematic carrier phase and code-based RAIM. The ellipses represent the associated probability error distributions, with carrier phase being the smaller white ellipse and code-based being the larger shaded ellipse. In Figure 4.3 equivalent thresholds were set, with the solid line representing kinematic and the dashed line representing code-based RAIM. As the ellipses move up the failure mode axis from the normal condition to the failure condition, it is easy to see that the carrier phase ellipse would exceed the threshold (solid line) long before the code-based ellipse exceeded its threshold (dashed line). Thresholds can be set to meet a given false alarm rate or to meet

the accuracy requirement. However, it not always possible to meet both, as depicted in Figure 4.3. It is important to note that when the ellipses move above the accuracy requirement, the kinematic ellipse has completely passed the threshold setting, while the code-based threshold is still within probability of error ellipse. It is the capability to establish tighter thresholds that gives carrier phase RAIM a distinct advantage over code-based RAIM.

Before kinematic RAIM is used, the aircraft receiver must solve for the integers as discussed in Chapter II. This is accomplished once the aircraft enters the integrity beacon bubbles, because the six or more independent measurements must agree with each other within a couple of centimeters. To achieve an integrity level better than 1×10^{-9}, the integrity protection radius would have to be set at approximately 30 cm, which is well within the minimum accuracy requirements of 60 cm (vertical) for CAT IIIC approach. Figure 4.4 illustrates this idea.
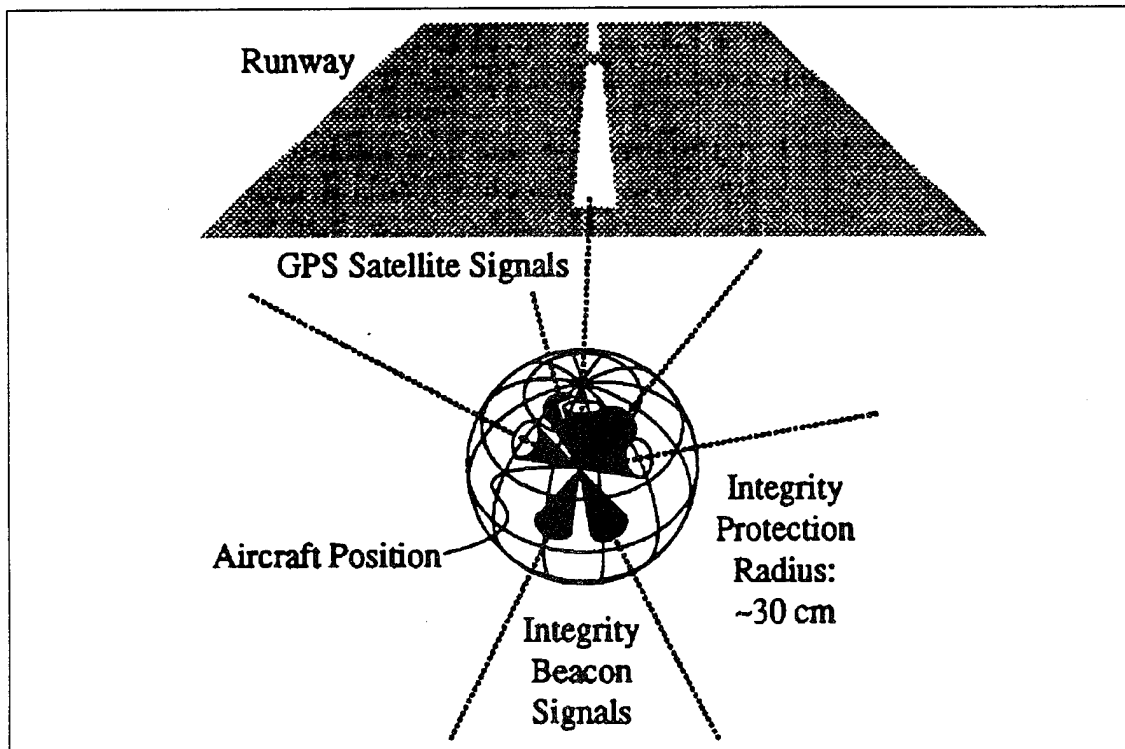

Figure 4.4 Integrity Protection Radius for IBLS From Ref. [20]

B.   OHIO UNIVERSITY'S CODE-PHASE DGPS

Ohio University has developed two different approaches to DGPS precision landing systems.   The first system they developed was a carrier phase based DGPS system that uses a least squares floating solution for navigation until the integer ambiguities are resolved.   This is virtually the same as E-Systems version presented in Section D of this chapter.   Ohio University is currently refining a code-phase DGPS system, which is discussed in the following paragraphs.

1.   System Description /Operation

Ohio University's DGPS system consists of a ground reference station and a VHF data link.   This system is based on both the ground reference station and the airborne platform using a narrow correlator receiver.   A ground reference station in the vicinity of the landing strip is required for this system to operate.   One ground reference station is capable of simultaneous serving all runways within a 20 nautical mile radius, provided the relative vector between the ground reference station antenna and the runway intercept point (RPI) is precisely known [Ref. 22].   The ground reference station receives the signals from all satellites in view.   This system differs from a traditional DGPS ground reference station. A traditional ground reference station calculates and then broadcasts a single message with the differential corrections for all satellites in view, whereas this system generates two separate messages that are broadcast to all airborne users neither of which contains standard differential correction information.

The first message contains the raw measurement data from the ground reference station.   This message consists of the measurement epoch, satellite vehicle identification, unfiltered pseudorange measurement, and the Integrated Doppler shift for all satellites in view.   The airborne processor performs the standard differential calculations necessary to determine the Selective Availability (SA) range correction, which reduces the transmission data requirements.

The second message consists of the derived Selective Availability range rate corrections. These range rates are calculated for each satellite, which can be using the difference between two successive Integrated Doppler measurements while accounting for the known satellite motion over the same period [Ref. 22].

2. Performance Against RNP Requirements

a. Accuracy

Ohio University has conducted several flight tests resulting in several hundred approaches. In addition, the Carrier Suitability Department at Naval Air Test Center, Patuxent River, MD, has also been using Ohio University's code to conduct numerous flight tests over their own. The accuracy results from Ohio University's latest flight test are given in Table 4.2. There were 50 autolandings performed over a two day period. The versatility of the system to support multiple runways was demonstrated by performing approaches to three different runways, without requiring any change in the ground station or the aircraft Flight Control Computer (FCC). The most promising aspect of this system is that it exceeds the accuracy requirements for RNP CAT III approaches and you do not have to solve for integer ambiguities.

Total System Error	Vertical 100ft	Lateral 100ft	Vertical 50ft	Lateral 50ft
Sigma σ	0.947 m	1.44 m	0.947 m	1.44 m
μ	-0.147 m	-0.539 m	-0.147 m	-0.539 m
$|\mu| + 2\sigma$	2.041 m	3.419 m	2.041 m	3.419 m
RNP	4.6 m	22.9 m	TBD	15.5 m

Table 4.2 Total System Error for 50 Autolandings by UPS Boeing 757

The flight path data for the 50 autolandings was plotted against the RNP 95% containment surface. As can be seen in Figure 4.5, at no time did the aircraft even come close to penetrating the containment surface.
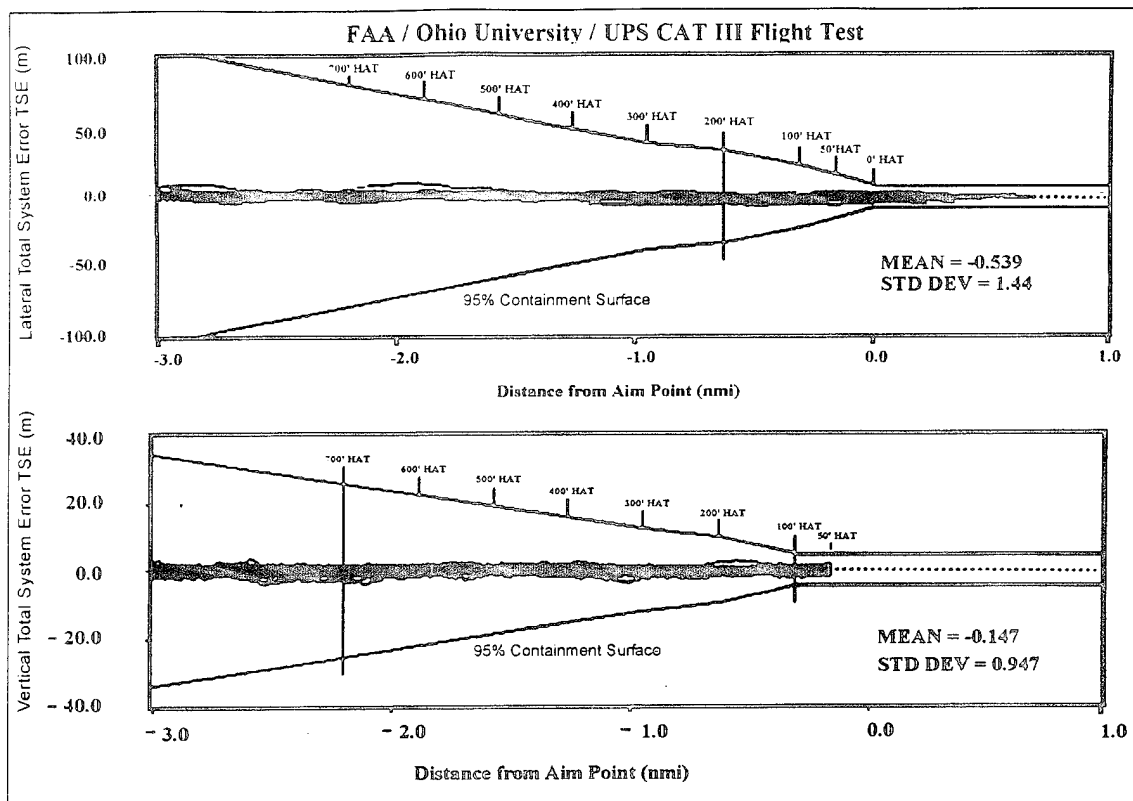
Figure 4.5 Total System Error vs. RNP Containment Surface for 50 Autolandings From Ref. [22]

b. Integrity

The main purpose of the flight test was to show the feasibility of code-based DGPS precision landing system to meet the stringent Category IIIA/B/C precision approach requirements. That is why very little was done to check the integrity of the system and why no ground-based integrity checks were set up for the flight test. However, there was some airborne integrity provided through Fault Detection and Isolation (FDI). FDI was also used to ensure the consistency of the Integrated Doppler measurements, which allows for detection of cycle slips providing additional integrity checks for the system. There were 50 precision approaches flown with no integrity problems encountered.

C. WILCOX'S NARROW CORRELATOR DGPS

Wilcox has been chosen to participate in the FAA flight test to demonstrate the feasibility of DGPS as a Category III precision landing system. For proprietary reasons, the information available on Wilcox's precision landing system was limited.

1. System Description /Operation

This system differs slightly from a traditional DGPS ground reference station, in that it uses a narrow correlator receiver and a carrier phase smoothing algorithm to substantially reduce the random noise and multipath effects. Wilcox's DGPS system consists of a ground reference station and a VHF data link. This system is based on both the ground reference station and the airborne platform using a narrow correlator receiver. A ground reference station in the vicinity of the landing strip is required for this system to operate. One ground reference station is capable of simultaneously serving all runways within the reception range of VHF data link, provided the relative vector between the ground reference station antenna and the runway intercept point (RPI) is precisely known. The ground reference station receives the signals from all satellites in view.

2. Performance Against RNP Requirements

a. Accuracy

Wilcox has flown several hundred instrument approaches to demonstrate the capability of their system. In September of 1993, forty instrument approaches were flown to runways 28 and 16 at Wallops Flight Facility in Virginia. Of the forty approaches, thirty one were hands-off automatic landings. The system exceeds the RNP requirements for accuracy [Ref. 23]. Please refer to Table 4.3 below.

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Total System Error	Vertical 100ft	Lateral 100ft	Vertical 50ft	Lateral 50ft
$|\mu| + 2\sigma$	3.4 m	2.7 m	3.4 m	2.7 m
RNP	4.6 m	22.9 m	TBD	15.5 m

Table 4.3 Wilcox Total System Error, 33 Autolands After Ref. [23]

b. Integrity

The main purpose of the flight test was to show the feasibility of code-based DGPS precision landing system to meet the stringent Category IIIB precision approach requirements. That is why very little was done to check the integrity of the system. There were 40 precision approaches flown with no integrity problems encountered. During the FAA flight test demonstrations, Wilcox will be using RAIM, 32 bit CRC, and multiple monitor comparison to provide high integrity for the system.

D. E-SYSTEMS

1. System Description /Operation

E-Systems has proposed a carrier phase DGPS system that does not use any pseudolites. The system is composed of a ground reference station and a VHF data link. The ground station and the airborne platform use an Ashtech Z-12 DGPS receiver. The airborne receiver is expected to receive the DGPS signal at approximately 19 miles. Using the DGPS signal, the airborne receiver will calculate a floating integer ambiguity solution. At approximately 10 miles from the runway the airborne receiver will start converging on the correct integer ambiguity, with the fixed ambiguity solution obtained before reaching the Final Approach Fix (approximately 5 miles from runway). This is graphically depicted in Figure 4.6 below.
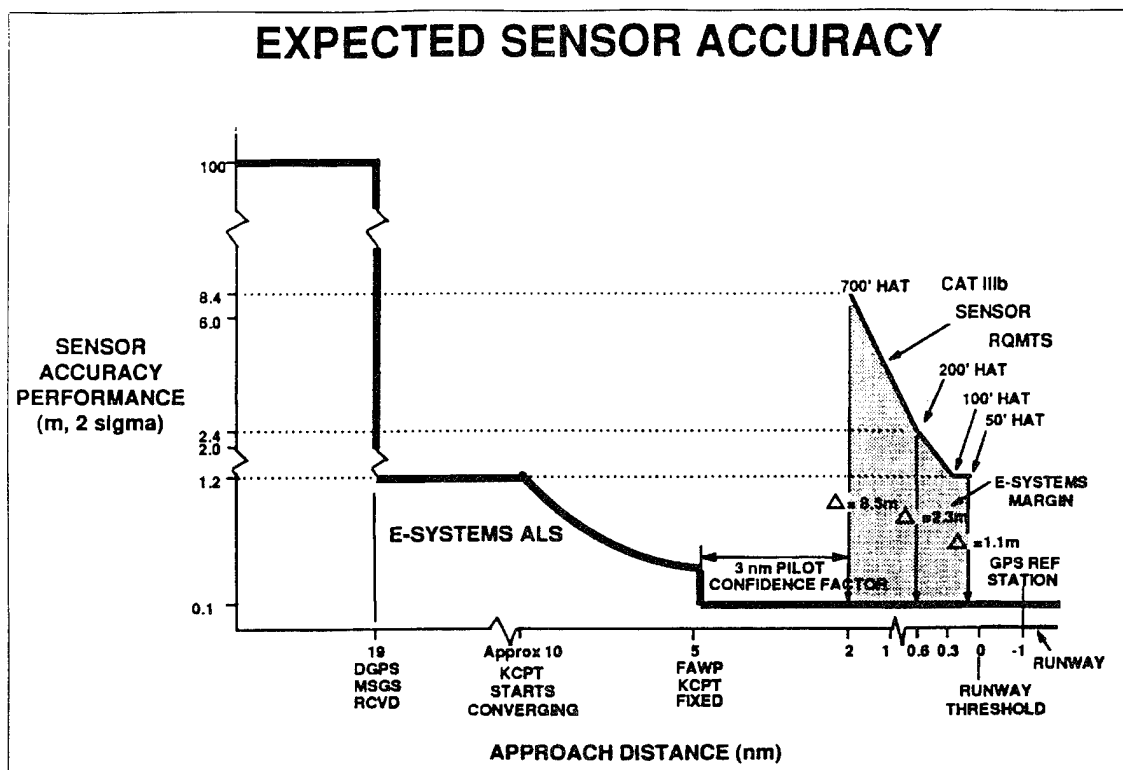
Figure 4.6 E-Systems Accuracy Profile From Ref. [24]

2. Performance Against RNP Requirements

It should be noted that E-Systems is participating in the FAA flight demonstrations this year to demonstrate the feasibility of Category IIIB approaches using DGPS as the navigation source. This has resulted in E-Systems being very careful about what information they make available for the general public at this particular time, limiting the depth of this evaluation.

a. Accuracy

E-Systems has conducted numerous simulations to verify and validate their system. In addition, on May 23, 1994 a test flight was conducted using their system. After reviewing the flight test data, E-Systems came to the following conclusions [Ref. 24]:

- Real Time ambiguity resolution for all approaches by at least the 4.0 nmi prior to threshold, after being reset at 10 nmi.

- Wide lane and L_1 ambiguities remained fixed after 2 minutes for balance of approach

- Accuracy was well within expected limits

- The results indicate that the same sets of ambiguities were resolved for both the real time and post processed data

Once the integer ambiguities have been found, the system easily meets all the accuracy requirements of the RNP. Please refer to Figure 4.7 for a plot North, East, and Up versus a run time of 300 seconds for the flight test conducted on 23 May, 1994.

b. Integrity

As with the Stanford system, the accuracy of carrier phase measurements provides for greater integrity by allowing the thresholds to be set tighter. E-Systems is using both ground equipment integrity monitoring and airborne equipment integrity checking. The ground equipment searches for and identifies bad satellites, as well as insuring the integrity of the VHF data link signal and data. The air borne equipment verifies the integrity of the uplinked data, performs RAIM, issues integrity alarms and warning flags if sensor error exceeds 2.3 meters for more than 2 seconds.
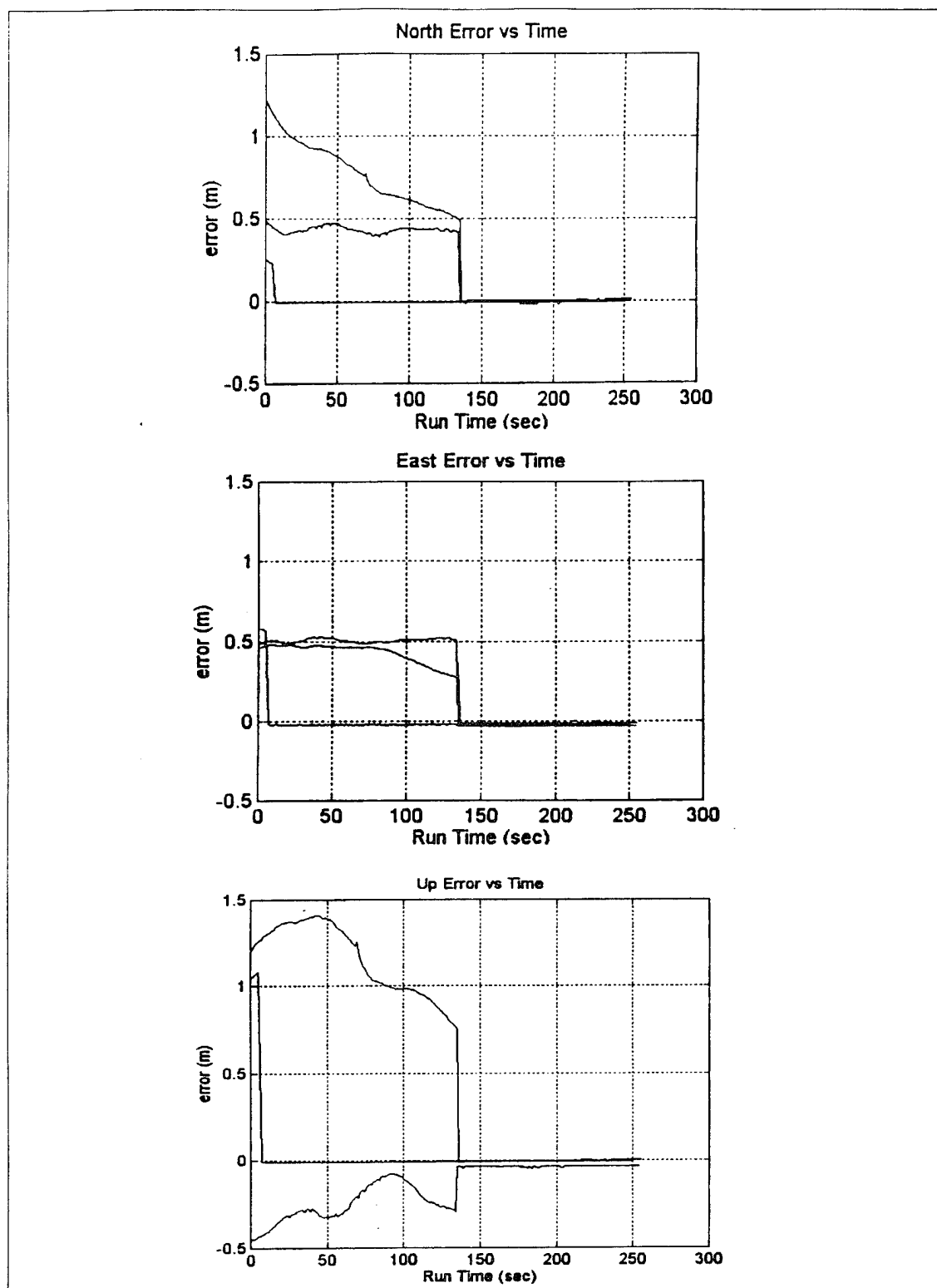
Figure 4.7 E-Systems North, East, and Up Errors vs. Run Time From Ref. [24]

E. WIDE AREA AUGMENTED SYSTEM (WAAS)

The Wide Area Augmented System is a DGPS system that is designed to cover the entire United States. It uses 26 ground stations located around the United States (providing a U.S. average correction) and a geostationary satellite to replace the ground reference station and VHF data link. This satellite would provide the required DGPS corrections data to all the aircraft. The problem with this system is that errors such as tropospheric and ionospheric delays vary from area to area, which means the broadcasted DGPS corrections will not be as accurate as traditional DGPS. This limits WAAS to Category I approaches and requires a local area DGPS ground station to meet the accuracy requirements for Category II/III approaches [Ref. 25].

F. DGPS COMMON CHARACTERISTICS

All DGPS systems use GPS as their starting point. In addition, all the systems being reviewed in this paper also have a ground reference station and a data link operating in the VHF radio frequency in their architecture. It is this commonalty that allows the following requirements to be discussed relative to DGPS in general, instead of addressing them system by system.

1. Meeting RNP Requirements

As discussed in Chapter III, the RNP uses accuracy, integrity, availability, and continuity as the four main parameters in defining the requirements for a precision approach. Accuracy and integrity are system dependent, but availability and continuity for the most part are dependent on the functioning Global Positioning System.

a. Availability

The major factor that determines the availability of DGPS precision landing system, as with most GPS based systems, is the number of satellites within view at a particular location at a particular time, which is often referred to as the satellite constellation availability. The satellite constellation availability has been calculated at

99.80%, when defining constellation availability as 4 or more operational satellites in view above a mask angle of 7.5 degrees and having a VDOP of less than 4.5 [Ref. 26, p. H-3]. If the DGPS system uses RAIM, the minimum number of satellites increase to five. This number is slightly less than the 99.990% required for a primary site availability requirement or the 99.9999% required for a combined primary/alternate site requirement discussed in Chapter III.

The satellite constellation availability does meet all of the DoD requirements for availability except for shipboard operations which is currently set at 99.90%. However, by reducing the mask angle or increasing the minimum VDOP it is possible to increase the satellite constellation availability, which is simply changing the definition. The availability of the system can also be increased by adding some satellites to the constellation. Either of the these options are viable, but it may make more sense to just accept the slightly lower availability figure for shipboard operations. The effect on shipboard operations by reducing this availability should be looked into, but will not be addressed any further in this paper. Stanford University's IBLS has demonstrated the ability to accept a VDOP as high as 18 with no apparent effect on the accuracy of the system [Ref. 20]. The more advanced technology is capable of handling a higher VDOP, so reducing the required VDOP in the definition doesn't necessarily mean a reduction in accuracy.

There is also a very small contribution to the degradation of availability caused by the expected failure rates of the ground reference station and DGPS data link. This is because these systems are composed of solid state electronics and have a very low failure rate.

b. Continuity

As with availability, continuity is fairly uniform among all DGPS systems, with the satellites in view as the major factor. The continuity for a navigation solution (four satellites required) over the standard 2.5 minute approach interval is 99.99924% or a

7.60×10^{-6} probability that there will be less than four satellites in view and operational during the approach [Ref. 26, p. H-3].

The ground reference station, data link and aircraft avionics also contribute an extremely small amount to the overall DGPS probability of failure. The continuity associated with this equipment can be estimated with the following formula [Ref. 26]:

$$(33) \quad P_{fail} = \frac{0.041666667}{MTBF}$$

where,

P_{fail} is the probability of failure during a standard approach

0.041666667 is the 2.5 minute standard approach converted to hours

MTBF is the Mean Time Between Failure expressed in hours.

Using a conservative MTBF of 4,000 hours for the data link and accounting for a back-up (redundancy required for CAT III approaches) data link (in parallel), the probability that both would fail works out to be 1.1×10^{-10}, which is indeed extremely small when compared to the satellite system. The probability of failure numbers are similar for the ground station and aircraft avionics as well.

There is another factor that can degrade the continuity of a system. This factor is called the false alarm rate. As discussed in Chapter III, there are established limits for this factor as well. The higher accuracy of kinematic carrier phase measurements allows the system to establish tighter thresholds on false alarm rates improving the continuity of this system.

Taking all of this into account, the probability of failure exceeds the RNP requirement of 1×10^{-4} for the same standard 2.5 minute approach.

2. Meeting DoD Requirements

The most of the requirements outlined in the MNS and DPALS are met or exceeded by any of the DGPS systems reviewed in this paper. The common characteristics that address those requirements are discussed below.

a. Logistics

(1) Set up Time. The set up time for these systems is less than two hours, with one hour typically being minimum set up time. The major factor in the set up time is the self surveying required for the ground reference station, which is approximately one hour.

(2) Battery Power. Since these systems are in the developmental stages, the ground reference stations are usually composed of a laptop computer and a GPS receiver, both of which have the existing capabilities to operate for several hours on internal battery power. Stanford University has been using a standard car battery for its ground station and could operate for at least six hours. Stanford's pseudolites are capable of running for over 12 hours on a 9 volt battery. Current technology can easily meet the 4 hour threshold established in the DPALS.

(3) Supply System Demands. The adoption of a DGPS system would not place any additional demands on the supply system. Since GPS and computers are widely used in the DoD, many of the components to these systems are already available in the supply system. Actually, the adoption of one standard precision landing system across all of the services would greatly reduce the requirements on the supply system and significantly contribute to the use of a common DoD logistics support system.

(4) Deployability. All of the systems are easily deployable. The Marine Corps uses the Marine Air Traffic Control and Landing System (MATCALS) as a deployable system. The TPN-22 is the radar that provides the automatic landing system capability. The radar is 12 ft long, 8 ft wide, 6 ft tall, and weighs 5,732 lbs. A DGPS system can provide the same capabilities, while only requiring the same space as a large laptop computer and is capable of being carried by one person. All of these systems meet the deployability objectives discussed in Chapter III.

Shipboard operations pose a special problem for the Stanford's IBLS system because the pseudolites are set up on both sides of the final approach path. With shipboard operations, the final approach path is over water and the ship is also moving making it impossible to simply place the pseudolites along the flight. However, there are several solutions to this problem.

First, the pseudolites could be mounted on each end of the aircraft carrier, with directional beacons to reduce any radio interference and detection probability. Stanford has shown that the integers can be held for normal traffic patterns maneuvers, including banking maneuvers up to 60 degrees. This would require the aircraft to pass over the aircraft carrier prior to landing, but only when an automatic landing was to be performed since Stanford's standard DGPS signal would be accurate enough for all other landings.

Another solution, was a towed buoy. Dr. Clark Cohen at Stanford University, thought it would be relatively simple to develop a towed buoy for the pseudolites [Ref. 27]. Again, the buoys would only have to be deployed to conduct automatic landings.

Finally, an aircraft carrier is never deployed without escort ships of some type. The pseudolites could be mounted on an escort ship, with the escort ship located underneath the standard holding pattern for the aircraft carrier. As with the other options, this would only be required of automatic landings.

b. Transportation

All of the DGPS systems require a ground reference station and a data link to be located in the vicinity of the intend runway (approximately 20 nmi). Although these systems are still in the development stage, it is possible at present to pack an entire ground reference station and data link into a large laptop computer carrying case.

Stanford University's system also includes two pseudolites that are the size of half a basketball and require cable to be run between the pseudolites and the ground reference station. The cable and the pseudolites add approximately another 150 lbs. Even with the additional weight requirements for Stanford University's system, all of these systems are capable of being transported on personnel on foot, which meets the DoD objective.

c. Manpower, Personnel, and Training

The minimum number of personnel to set up the system is one, with three being optimum to reduce set up time. Once the initial setup is completed, no personnel are required to operate the system. It will take no more than two days to train the personnel on the complete setup and operation of this system [Ref. 27].

d. Mapping, Charting, and Geodesy Support

The Global Positioning System was developed for the DoD and meets all of these requirements. Currently GPS use WGS-84 as its datum reference. The DGPS systems augment the GPS system and have virtually no effect with respect to these requirements.

e. Command, Control, Communications, Computers, and Information (C^4I)

GPS has been in use by the DoD for over a decade. It was used extensively in the Gulf War to aid in C^4 I. The DGPS systems looked at in this paper augment our current C^4I and are not expected to present any additional problems or complications for our C^4 I system.

f. Security

Concerning a precision landing system, security refers to ability to protect the navigation signal from jamming and spoofing. The DoD understood the potential threat from jamming and spoofing when GPS was being designed, and this is why we have the

encrypted Y-code on both the L_1 and L_2 frequencies. The following paragraphs discuss the security capabilities of DGPS.

(1) Jamming. GPS uses a spread spectrum signal, which provides a 43 dB jammer-to-signal ratio just due to the processing gain. This number can be increased significantly by incorporating anti-jamming circuitry and null steering antennas as well as other sophisticated technology. To illustrate this, consider a jammer located only fifty miles away and a GPS receiver using the P-code. In order for the jammer to be effective, it would have to be capable of generating at least 25 watts of jamming power. This amount of power would produce an easily identifiable signature, which also can be easily targeted and destroyed. The VHF data link is susceptible to jamming as well, but because of the close proximity between the ground station and the aircraft a high power jammer would be required to interrupt the navigation signal.

(2) Spoofing. This refers to how easy it is to generate a false navigation signal that the receiver believes to be true. The use of the encrypted Y-code, which is available to military users, makes it virtually impossible to spoof without having the encryption key. The data link is VHF and can be easily adapted to plug into any of the COMSEC equipment within the DoD, giving it the same protection against spoofing as the GPS signals. Stanford University's system uses pseudolites, transmitting on the same frequency as the satellites. These pseudolites are also easily adapted to accept DoD COMSEC equipment to encrypt their signals as well.

(3) Detection. Stanford's pseudolites are beacons which can be detected. However, they only transmit $1\mu W$, which reduces the detection range to a few hundred meters of ground based detection equipment. As mentioned above we can reduce this by using the encrypted Y-code. The data links are VHF transmissions, which are also easy to detect, but the use of low power transmitters, directional antennas, and the encrypted Y-code will significantly reduce the probability of detection.

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These systems can be configured to meet or exceed current DoD capabilities for communication security.

g. Standardization and Interoperability

With the adoption of a GPS based precision landing system, interoperability between the services is easily achievable. It will also simplify all aspects of aircraft navigation by providing a single and seamless type of navigation from take off to landing. The FAA has approved a GPS Special Category I approach, and ICAO is following in the same footsteps. With all of the time, effort, and money being spent on DGPS and its enormous potential, it seems inevitable that DGPS will be implemented and accepted as an international standard. This will only add to the military's capability to operate in the national and international airspace.

h. Operational Environment

The DGPS systems reviewed in this paper are capable of working in all type of weather. The only limitation on terrain is that the data link antenna must have a clear line of sight to the aircraft. For the Stanford University system, the pseudolites must also have a clear line of sight to the aircraft within the integrity bubble radius. The only limitation to the number of aircraft these systems can support at any one time is aircraft spacing requirements.

i. Cost

(1) Stanford University. This system is still being refined, but the people at Stanford believe that this system can be installed at cost of approximately $200,000.00 per runway end, which includes all required redundancies for a Category IIIC approach. This figure is approximately 80% cheaper than an ILS or MLS system as discussed at the ISPA '95 conference in Braunschweig, Germany [Ref. 27].

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(2) Ohio University. The code and system hardware are being refined. The cost for the ground reference station and data link, including software, is approximately $80,000.00, which is capable of servicing multiple runways and possibly multiple airports as well.

(3) Wilcox. A price quote was not available, but the hardware and software designs are very similar to Ohio University, so an approximate cost of $80,000.00 should be very reasonable. This system is also capable of supporting multiple runways

(4) E-Systems. Again, a price quote was not available. The hardware requirements are virtually the same as Ohio University and Wilcox, but the software code is substantially different. However, the overall cost should be approximately the same as Ohio University at $80,000.00.

It should be noted that airborne equipment required for all these systems is a approximately $70,000.00 per aircraft, because they are typically sold with the vendor's Flight Management System. Furthermore, if additional redundancy is required to be installed, the cost may double.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

To provide some clarity, my conclusions will broken into three areas: Differential GPS and RNP requirements, Differential GPS and DoD requirements, and general comments.

1. Differential GPS and RNP Requirements

Current Differential GPS technology is more than capable of meeting the accuracy requirements for all categories of precision approaches, to include the most demanding Category III requirements. Continuity and availability requirements can be met using DGPS. The required redundancy in avionics and ground station equipment for precision landing systems has resulted in the GPS satellite constellation becoming the major factor involved in determining the continuity and availability.

Until recently, the primary focus has been on the meeting the accuracy requirements for Category III approaches. With this aspect of DGPS under control, the commercial sector is starting to seriously address the integrity issue. Integrity, as with accuracy, is a system dependent characteristic. Stanford University has addressed this issue, and is boasting a level of integrity better than $1x10^{-9}$, exceeding the RNP requirements. Even though the other systems have not specifically addressed integrity, current trends in the refinement and development of RAIM algorithms is very encouraging.

2. Differential GPS and DoD Requirements

In addition to the technical requirements established by the RNP, the DoD places additional requirements on a precision landing system. All of the DGPS systems evaluated were capable of meeting or exceeding the Measures of Effectiveness (MOEs)

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identified in Chapter III. Please refer to Table 5.1 for an overview of DGPS systems versus DoD requirements.

Measures of Effectiveness	Meeting DoD Requirements for each Scenario			
	Fixed Base	Tactical	Clandestine	Shipboard
Aircraft Accident Rate	YES	YES	YES	YES
Decision Height	YES	YES	YES	YES
Time to Alarm	YES	YES	YES	YES
Availability	YES	YES	YES	TBD
Number of Personnel required to Operate System	YES	YES	YES	YES
Number of Personnel required to Support System	YES	YES	YES	YES
Preventative Maintenance	YES	YES	YES	YES
Aircraft Capacity	YES	YES	YES	YES
Coverage	YES	YES	YES	YES
Range	YES	YES	YES	YES
Probability of Detection	N/A	YES[1]	YES[1]	YES[1]
Spoofability	N/A	YES[1]	YES[1]	YES[1]
Effective Jamming Range	N/A	YES[1]	YES[1]	YES[1]
Setup Time	N/A	YES	YES	N/A
Sustainability	N/A	YES	YES	N/A
Battery Power Operations	N/A	YES	YES	N/A
Transportability	N/A	YES	YES	N/A
NOTE: [1] indicates evaluation was performed on an unclassified basis, and further research based upon classified analysis is required.				

Table 5.1 DGPS vs. DoD Requirements

3. General

The adoption of a DGPS precision landing will meet the requirements identified in the DPALS. In addition, it will provide the pilot with virtually seamless navigation from departure to arrival. GPS technology is used extensively throughout the DoD and the

civilian world today. The demands on the logistics support system should be reduced by only having one system to support for all the services and the availability of GPS components already in the supply system.

B. RECOMMENDATIONS

I believe the robustness, ease of operation, and the fact that integer ambiguities do not have to be solved make the Ohio University and Wilcox systems the front runners and especially suited for tactical, shipboard, and clandestine operations. For fixed based operations, increased integrity may be a key concern. If this is the case and increased cost is not a major concern, then I believe a combination of Stanford's integrity beacons and the Ohio University or Wilcox system would be a perfect mix. The code-based systems can easily provide up to Category II accuracy requirements to all runways (meeting almost all expected weather conditions), while providing excellent integrity, whereas the integrity beacons could be installed on the primary runway to provide Category III accuracy with greater integrity.

APPENDIX A. TROPOSPHERIC CORRECTION MODEL

Using the Hopfield model for altitude variation of the Index of Refraction, Black developed "An Easily Implemented Alogrithm for the Tropospheric Range Correction" [Ref. 28]. The following equation is used to model tropospheric range error correction:

$$(34) \quad \Delta s = \Delta s_d + \Delta s_w$$

where Δs represents the tropospheric delay and Δs_d and Δs_w represents the tropospheric delay due to "dry air" and "wet air" respectively. It should be noted that dry air contributes 90% of the total tropospheric delay, whereas, wet air contributes only 10% of the total tropospheric delay. Now Δs_d and Δs_w are calculated using the following equations and constants:

$$(35) \quad \Delta s_d = 2.343 P \left[\frac{(T-4.12)}{T} \right] I(h_d, E)$$

$$(36) \quad \Delta s_w = k_w I(h_w, E)$$

$$(37) \quad I(h, E) = \sqrt{1 - \left[\frac{\cos E}{1 + (1 - l_c)\frac{h}{r_s}} \right]^2}$$

$$(38) \quad r_s = 6378137 \; meters$$

$$(39) \quad P = 1 \; atmosphere$$

$$(40) \quad T = 15^\circ \; C$$

$$(41) \quad h_w = 13,000 \; meters$$

$$(42) \quad h_d = 148.98(T - 4.12) \; meters$$

$$(43) \quad l_c = 0.85$$

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$$(44) \quad k_w = 0.2$$

It should be understood that l_c and k_w are empirical constants and the value of 0.85 for l_c is valid only for elevation angles (E) above five degrees. Furthermore, k_w has several empirical values with 0.2 being valid for spring and fall in the mid-latitudes. When the elevation angle (E) is above 40° this model is practically exact. The worst error is approximately 0.045 m and occurs when the elevation angle (E) is between 5 and 10 degrees. The tropospheric error is the same for both levels of GPS service.

APPENDIX B. EXTENDED KALMAN FILTERING

The GPS observable range is a nonlinear function. Therefore we must look at how these nolinearities can be treated. The observation equations are given by:

(45) $\quad \mathbf{X}_{k+1} = f(\mathbf{X}_{k/k})$

and

(46) $\quad \mathbf{Z}_k = h(\mathbf{X}_{k/k}) + v_k$

In order to use a linear filter, these equations are expanded and only the first order terms are kept, resulting in the following equations:

(47) $\quad \mathbf{X}_{k+1} = \Phi_k(\mathbf{X}_k)$

where

(48) $\quad \Phi_k = \left. \frac{\partial f}{\partial \mathbf{X}} \right|_{\mathbf{X} = \hat{\mathbf{X}}_k}$

and

(49) $\quad \mathbf{Z}_k = H_k \bullet (\mathbf{X}_k) + \mathbf{v}_k$

where

(50) $\quad H_k = \left. \frac{\partial h}{\partial \mathbf{X}} \right|_{\mathbf{X} = \hat{\mathbf{X}}_{k/k-1}}$

It is important to define the state vectors and matrices. A state error vector is defined by $\tilde{\mathbf{X}}_k = \hat{\mathbf{X}}_k - \mathbf{X}_k$, and a predicted state error vector is defined by $\tilde{\mathbf{X}}_{k+1/k} = \hat{\mathbf{X}}_{k+1/k} - \mathbf{X}_{k+1/k+1}$. The measurement noise covariance matrix is defined by $R_k = E\left[\mathbf{v}_k \bullet \mathbf{v}_k^T \right]$. The covariance of the state error matrix is given by $P_k = E\left[\tilde{\mathbf{X}}_k \bullet \tilde{\mathbf{X}}_k^T \right]$, and the predicted covariance of the state error matrix is given by $P_{k+1/K} = E\left[\tilde{\mathbf{X}}_{k+1/k} \bullet \tilde{\mathbf{X}}_{k+1/k}^T \right]$ [Ref. 29].

In order to continue we need to identify some of the Kalman filter equations, which are given by the following:

(51) $\quad P_{k+1/k} = \Phi_k P_k \Phi_k^T + Q_k$

(52) $\quad G_k = P_{k+1/k} H_k^T \left[H_k H_k^T P_{k+1/k} + R_k \right]^{-1}$

(53) $\quad P_k = P_{k/k-1}\left[I - G_k H_k \right]$

(54) $\quad \dot{\hat{X}}_{k+1/k} = f\left(\hat{X}_{k+1/k} \right)$

(55) $\quad \hat{X}_{K+1/k+1} = X_{k+1/k} + G_k \left[Z_{k+1} - \hat{X}_{k+1/k} \right]$

It takes time for the GPS receiver to process the GPS signals and determine the observation Z_i. We need to predict ahead in time so that real time information is provided to the navigation equipment and the pilot. The Kalman filter uses a recursive linear algorithm to update a predicted $\hat{X}_{k+1/k}$. The Kalman filter requires an intial state, which is given by the following equation:

(56) $\quad \hat{X}_0 = Z_0$

After the initialization, $\hat{X}_{k+1/k+1}$ is determined by the following equation:

(57) $\quad \hat{X}_{k+1/k+1} = \hat{X}_{k+1/k} + G\left[Z_{k+1} - \hat{X}_{k+1/k} \right]$

The gain matrix, G, is updated with every estimate. By allowing G to go to the extreme of zero, it can be seen that the new observation is completely ignored and that the estimation of the system state is simply the old prediction, $\hat{X}_{k+1/k}$. Whereas, if you let the gain matrix go to 1, the old prediction will cancel and only the observation, Z_{k+1}, will be used. Therefore, the gain matrix is a gauge of the validity of the new

measurement. Now $\hat{X}_{k+1/k}$ is the prediction of $\hat{X}$ at time k+1 using all the information available at time k. This prediction is based upon the following equation:

$$(58) \quad \hat{X}_{k+1/k} = \Phi\hat{X}_{k/k}$$

where Φ is the transition matrix. A standard GPS receiver uses an eighth order state vector. To keep things simple, a sixth order state vector X will be used.

$$\mathbf{X} = \begin{bmatrix} X \\ \dot{X} \\ Y \\ \dot{Y} \\ Z \\ \dot{Z} \end{bmatrix} \Rightarrow \mathbf{X}_{k+1/k} = \Phi\mathbf{X}_{k/k} \text{ (linear state form)}$$

where

$$\Phi = \begin{bmatrix} 1 & T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & T \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Remember that the range observation equation is nonlinear for GPS in the states and is given by:

$$(59) \quad Z_k = \sqrt{x_k^2 + y_k^2 + z_k^2}$$

The observation matrix, H_k , can be derived using equation 51 yielding the following equation:

$$(60) \quad H_k = \begin{bmatrix} \dfrac{x_k}{\sqrt{x_k^2+y_k^2+z_k^2}} & 0 & \dfrac{y_k}{\sqrt{x_k^2+y_k^2+z_k^2}} & 0 & \dfrac{z_k}{\sqrt{x_k^2+y_k^2+z_k^2}} & 0 \end{bmatrix}$$

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This requires the observation matrix, H, to be calculated at each measurement. However, by doing this, the recursive Kalman filter equations have been extended to cover the nonlinear case[Ref. 29].

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